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AMERICAN GEOPHYSICAL UNION

TRANSACTIONS OF 1943

PART I

TWENTY-FOURTH ANNUAL MEETING
APRIL 23 AND 24, 1943
WASHINGTON, D. C.

REPORTS AND PAPERS

GENERAL ASSEMBLY AND
SECTIONS OF GEODESY, SEISMOLOGY, METEOROLOGY,
TERRESTRIAL MAGNETISM AND ELECTRICITY
OCEANOGRAPHY, VOLCANOLOGY,
AND TECTONOPHYSICS

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TRANSACTIONS OF 1943

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INTRODUCTION

The American Geophysical Union was established in 1919 as the American Committee of the International Union of Geodesy and Geophysics, and its Executive Committee is the Committee on Geophysics of the National Research Council. The objects of the Union are to promote the study of problems concerned with the figure and physics of the Earth, to initiate and coordinate researches which depend upon international and national cooperation, and to provide for their scientific discussion and publication. In the accomplishment of these objects, the Union is divided into Sections following the plan of organization of the International Union of Geodesy and Geophysics. There are now eight Sections, namely, (a) Geodesy, (b) Seismology, (c) Meteorology, (d) Terrestrial Magnetism and Electricity, (e) Oceanography, (f) Volcanology, (g) Hydrology, and (h) Tectonophysics. A Section of Geophysical Chemistry was discontinued May 31, 1924, as the International Union had failed to provide such a Section. The Section of Hydrology was established November 15, 1930--matters pertaining to scientific hydrology referred to the American Geophysical Union had been previously looked after by special committees on Hydrology. The Section of Tectonophysics was established April 9, 1940, for the purpose of promoting and encouraging research of fundamental importance to our knowledge of Earth-structure not covered in any one of the other Sections of the Union.

Annual assemblies of the Union and annual meetings of its Sections for the discussion of reports and for symposia are held each year. The first 13 assemblies and meetings--those in each of the years from 1920 to 1932--were held in Washington, D. C. Besides the annual general assemblies and meetings of each of the Sections held since 1933 in Washington, D. C., regional meetings of the Section of Hydrology were held at Berkeley, California (1933 and 1934), at Pasadena, California (1936), at Denver, Colorado (1937), at Spokane, Washington (1937), at Davis, California (1938), at Los Angeles, California (1938), at Spokane, Washington (1938), at Stanford University, California (1940), at Seattle, Washington (1940), at Sacramento, California (1941), at Dallas, Texas (1941), at Pasadena, California (1942), and at Corvallis, Oregon (1943). The transactions of annual assemblies and meetings through the ninth were published in the Bulletin series of the National Research Council as follows: Second, 1921, Bulletin No. 17; fourth, 1923, Bulletin No. 41; sixth, 1925, Bulletin No. 53; seventh, 1926, Bulletin No. 56; eighth, 1927, Bulletin No. 61; and ninth, 1928, Bulletin No. 68. Transactions of the tenth and eleventh annual meetings held in 1929 and 1930 were published in one volume in June 1930, and those of the twelfth, thirteenth, fourteenth, fifteenth, sixteenth, seventeenth, eighteenth, nineteenth, twentieth, twenty-first, twenty-second, and twenty-third annual meetings were published in June 1931, June 1932, June 1933, June 1934, August 1935, July 1936, July 1937, August 1938, July and August 1939, July and September 1940, July and August 1941, and August and November 1942, respectively, in the series of miscellaneous publications of the National Research Council. The present volume, Part I of the Transactions of 1943, also one of the miscellaneous publications of the Council, includes the proceedings of the twenty-fourth annual meetings, except for the Section of Hydrology which will be Part II, at Washington, D. C., in the Hall of Government of the George Washington University, April 23 and 24, 1943; Part III of the Transactions of 1943 will contain the proceedings of the joint regional meeting of the Section of Hydrology and the Western Snow-Survey Conference at Corvallis, Oregon, June 16, 1943. At the first, third, and fifth annual meetings in 1920, 1922, and 1924, respectively, there were no scientific papers presented; therefore, the transactions for these were not printed but were mimeographed for limited distribution only.

The present volume (Part I) contains 67 papers and reports, with discussions, presented at the twenty-fourth annual meetings in 1943 before the Union and before all the Sections except the Section of Hydrology. As in the Transactions of 1942, the minutes of the various meetings, with their appendices, are placed at the ends of the respective Parts. The total attendance of members and guests, despite the urgent demands upon all because of the war, was in excess of that registered, namely, 475.

Nine resolutions were adopted. These relate to (1) precise surveys and maps, (2) essential geophysical observations for duration of the war, (3) implementation of meteorology for war purposes, (4) establishment of more stations in oceanic areas and Antarctica in interest of daily and long-range forecasting, (5) Naval time-signal services, (6) adequate post-war program of seismological investigations, (7) practical post-war program in all branches of Geophysics, (8) ways and means of providing employment for geophysicists released from war effort during period of transition from war to peace, and (9) thanks to George Washington University for facilities extended for meeting.

The fifth award of the William Bowie Medal to OSCAR EDWARD MEINZER was made at the General Assembly. Brief memorials on three of the members who had died in the year since the

last meeting were read. The remainder of this session, on the afternoon of April 24, was devoted to a conference on and discussion of the projected program of the Commission on Continental and Oceanic Structure of the International Union of Geodesy and Geophysics. This Commission was formed at Edinburgh in 1936 with the instruction to devise, stimulate, and sponsor geophysical-geological studies of crustal structure on a world scale, in extension and in support of the similar but less extensive studies made by some of the national organizations adhering to the International Union.

The list of contents for the proceedings of each of the seven Sections published in this volume indicate the diversity of the several fields and the activity and progress in each.

The General Secretary edited the manuscripts for publication after some preliminary editing by the secretaries of Sections. The cost of publication was met through allotment by the National Research Council and annual dues of members. As in past years, the Union is grateful for quarters provided without cost by the Carnegie Institution of Washington at its Department of Terrestrial Magnetism. Each of the authors, except for a few who could not be reached, revised a carbon of the master-copy from which the Transactions were printed by the offset method. The final master-copy was prepared by J. J. CAPELLO and W. E. SCOTT and was planographed by the Kirby Lithographic Company of Washington, D. C. W. C. HENDRIX redrew many drawings and, with J. W. GREEN, looked after the large amount of photographic work required.

The American Geophysical Union has made every endeavor in the past year to increase the coordination and collaboration of interests, especially with the geophysicists of the Western Hemisphere and to maintain a considerable part of the continuity of the functions of the International Union of Geodesy and Geophysics, thus protecting for the future those international relations so essential to geophysical research. A recent quotation from a prominent geophysicist of California may be apt in this connection: "The Union, in my opinion, is to be congratulated for having the vision and courage to proceed with the (24th) annual meeting. The Nation needs more, not less, scientific endeavor."

In these days of total war, as never before, responsibility for continued attainment of geophysical knowledge falls with particular directness upon Americans. Now, as never before, American scientists personally benefit by affiliation with their fellow specialists and coworkers, since the individual worker is under a great hardship. Now, as never before, scientists in general of the Western Hemisphere need to affiliate and play their part not only in the immediate problems of applications to war-effort--to which the geophysicist is contributing effectively--but in the rehabilitation of international relations and endeavors particularly necessary to investigation of Earth-physics.

J. A. FLEMING, General Secretary,
American Geophysical Union

AMERICAN GEOPHYSICAL UNION

TWENTY-FOURTH ANNUAL MEETING

GENERAL ASSEMBLY

AFTERNOON SESSION

AWARD OF WILLIAM BOWIE MEDAL
MEMORIALS
CONFERENCE

Washington, D. C.
April 24, 1943

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FIFTH AWARD OF WILLIAM BOWIE MEDAL, MEMORIALS, AND CONFERENCE APRIL 24, 1943

AWARD OF THE WILLIAM BOWIE MEDAL

CITATION

Lorenz G. Straub

Mr. President: It is a great privilege and with deep pleasure that I present in behalf of the William Bowie Medal Committee the recipient of the award for 1943, the fifth recipient of this distinctive honor.

The William Bowie Medal carries with it the recognition for distinguished attainment and outstanding contribution to the advancement of cooperative research in fundamental geophysics. I am presenting one whose eminent career is singularly established in these high ideals.

He has long been the foremost authority of this country, and perhaps the world, on ground-water. He became Chief of the Division of Ground-Water in the Geological Survey in 1912, when the Division consisted of only himself and one or two others. From that time to the present he has directed his attention to the problems of ground-water and to the development of the science. Under his leadership his organization has grown to include nearly a hundred scientists, all of whom devote full time to this work. Always greatly interested in research, it has been through his initiative that a hydrologic laboratory was established in the Division, where studies are carried on of the physical properties of water-bearing materials.

A geologist by education, his natural traits include an extremely orderly mind and an engineering viewpoint. It has been through his leadership and his encouraging of coworkers that large strides have been made recently toward placing ground-water on a quantitative basis. This may be ultimately regarded as his outstanding accomplishment.

The Section of Hydrology of the American Geophysical Union owes much to his guidance in its formative years when as its first President he laid down an organization pattern which has provided a focal point for the growth of scientific hydrology in America.

He is an ardent believer in the scientific approach to problems and a strong advocate of the wide dissemination of scientific information. He is an excellent writer and has a long list of publications that contain original and important contributions to ground-water. Among the most outstanding of these are Water-Supply Papers 489 and 494, "Occurrence of ground-water in the United States" and "Outline of ground-water hydrology." His scientific achievements include the promulgation of the theory of compressibility and elasticity of water-bearing formations and the relation of these properties to the occurrence and recovery of ground-water. Outstanding also is his contribution to geophysics and the manifestation of his genius for organization and cooperation in the treatise "Hydrology" [Physics of the Earth Series of the National Research Council], in which he brought out an important volume by associating with himself 24 co-authors covering in a notable manner a broad field of science.

A spirit of cooperation and leadership is characteristic of him in the many organizations of which he is a member. Thus he is or has been at various times President of the Washington Academy of Sciences, President of the Geological Society of Washington, United States representative on the Executive Committee of the International Association of Hydrology, President of the International Commission on Underground Water, and a leader in many other scientific societies.

This electee, Mr. President, most assuredly has maintained a career of selfless, constructive, and cooperative endeavor and has added much to the structure of our knowledge of geophysics by his personal contributions, but even more by his stimulating influence upon his colleagues. It is with special pleasure that I present to you Dr. OSCAR EDWARD MEINZER.

Acting President L. H. ADAMS: In the name of the American Geophysical Union and acting for and on behalf of President W. C. LOWDERMILK, I present you herewith the William Bowie Medal, and I congratulate you on the achievements that have led to this award.

REPLY AND ACCEPTANCE

O. E. Meinzer

Mr. President and members of the Union: I certainly esteem it a very great honor to receive this award from the American Geophysical Union which contains in its membership such a large number of very distinguished and capable scientists. I accept the Medal with deep humility and a feeling of unworthiness but nevertheless also with a great feeling of encouragement and inspiration that you good friends have such confidence in me.

I feel that the geophysical enterprises on which I have been particularly engaged have been ones which were ripe for development so that not much was needed but a reasonable amount of energy and intelligence to get them started. That was certainly true of the Section of Hydrology. A few of us remember that prior to 1930 the International Union of Geodesy and Geophysics was urging the American Geophysical Union to establish a Section of Hydrology but that action on the part of our Union was postponed from year to year because it was felt there was not enough interest in hydrology to justify the organization of such a Section. Then in 1930 the Union organized a Section of Hydrology, and we were all overwhelmed with the response that we received and the place that it filled in the scientific set-up of this country. I think there were two policies that were perhaps quite effective. One was the organization of nine permanent Research-Committees on which were appointed an aggregate of about 115 men who were outstanding in their particular fields of hydrology and these men at once got to work actively in the Section. The other effective policy was to invite the hydrologists of the West to participate and to hold regional meetings, which they did.

In the International Association of Scientific Hydrology, we followed somewhat the same tactics. Up to the time that Dr. CHURCH became the head of the International Commission on Snow, the International Association of Scientific Hydrology essentially consisted of a rather small group of European hydrologists with hit-or-miss participation by some of us from the United States. Dr. CHURCH at once set about to make the International Association a really world-wide organization and in that he had the support of President LÜTSCHG, of Switzerland, and Vice-President SLETTENMARK, of Sweden--those two broad-minded men--so that when I was placed in charge of the International Commission on Subterranean Water I followed their tack. By the simple device of securing members from all adhering countries and advisory members from the non-adhering countries, we were certainly on the way to making the Commission a world-wide organization when the war came. The International Commission on Subterranean Water has, we feel, a special opportunity at this time in South America and Central America, in that we have there a field that is two and one-half times the area of the United States with great undeveloped resources of groundwater. Probably nothing will aid in the sanitary improvement of those countries more than the development of that ground-water by sinking wells for water-supply for municipalities. We have the cooperation of the Pan-American Union and the Coordinator of Inter-American Affairs, and it will probably be for some men younger than myself to carry that worth-while service to fruition by developing ground-water experts in Latin-American countries.

In the development of the Ground-Water Division of the United States Geological Survey and of the principles and technique of ground-water hydrology I have been supported by as brilliant and cooperative a group of young geologists and engineers as can be found anywhere. From the present perspective, as I look back over the years, it seems to me that our work has been in a sense preparatory to enable us to render service in the present great emergency. That preparation has consisted not only of the data that we have been collecting during the years and the technique of investigation that we developed, but also the nation-wide organization consisting of about 25 field-offices of the Ground-Water Division and the State agencies that have to do with water-resources, with all of which we are in close contact. This has enabled us to make numerous war-agency reports that were generally sound and practical and yet prompt. The magnitude of that work is in a way shown by the fact that our records indicate that we made about 500 reports on the development of water-supplies from wells for defense agencies of the Government prior to Pearl Harbor and to date the number of such reports for war purposes is in the neighborhood of 1600. We have made investigations and sent our men to all parts of the world wherever our troops and ships have gone, and in addition to the civilian service in this Hemisphere and in the islands of the Pacific, we have furnished ten of our best ground-water geologists for duty overseas with the Army.

Now I do not know, from the way you gentlemen [Acting President ADAMS and Dr. STRAUB] have been standing here so attentively, whether I was supposed to make such a long speech, but I have never had such a wonderful thing happen to me before and I may not have acted properly. However, I think my little speech would not be complete if I did not mention the encouragement and cooperation of my good wife who married me several months after I began to dabble with ground-water in 1906 and who has stayed married to me ever since.

Acting President L. H. ADAMS: The Union is proud of the name of WILLIAM BOWIE. I understand that Mrs. BOWIE is with us. I wonder if she will step forward so that she might be seen and recognized.

Mrs. WILLIAM BOWIE: I am too overcome to speak.

MEMORIALS

The audience stood in memory of those members who have died since the twenty-third annual meeting as indicated in the following list which was read by the General Secretary.

Name	Section-affiliations	Died
Edward Crosby Bebb	Meteorology, Hydrology	August 7, 1942
Richard Carlysle Cady	Hydrology	January 15, 1943
Max Harrison Demorest	Meteorology, Oceanography, Hydrology, Tectonophysics	November 30, 1942
Frederick Charles Ebert	Hydrology	February 23, 1943
George William Hawley	Hydrology	September 11, 1942
John Hedberg	Hydrology	August 3, 1942
Lawrence Joseph Henderson	Ex-officio (Chairman, Division of Foreign Relations of National Research Council)	February 10, 1942
William John Peters	Geodesy, Meteorology, Terrestrial Magnetism and Electricity, Oceanography, Hydrology, Volcanology	July 10, 1942
Walter Ford Reynolds	Geodesy	May 1, 1942
Robert Wilcox Sayles	Meteorology, Oceanography, Hydrology	October 1, 1942
David Grosh Thompson	Hydrology	February 19, 1943
Cyrus Fisher Tolman	Volcanology, Hydrology	October 12, 1942

Memorials regarding the life and work of three of these members who have so recently passed on from military and civilian activities were then presented as follows:

DAVID GROSH THOMPSON

O. E. Meinzer

DAVID GROSH THOMPSON was born in Lockland, Ohio, May 12, 1888, and died in his home in Washington, D. C., February 19, 1943. At the age of four his family moved to Evanston, Illinois, where his father was the editor of the Northwestern Christian Advocate. Mr. Thompson was graduated from Northwestern University in 1911, received a Master's degree from the University of Illinois in 1913, and also took graduate work in Chicago and Johns Hopkins universities. He served on the geological surveys of Illinois and Maryland, and was an instructor in Lehigh University and Goucher College. From 1917 until his death he served in the Ground-Water Division of the United States Geological Survey. In 1922 he was married to Frances E. Goodrich. He is survived by her and by their two sons, David Goodrich and Clifford Francis. He was a fellow of the American Association for the Advancement of Science and the Geological Society of America, and a member of the American Geophysical Union, Society of Economic Geologists, Geological Society of Washington, Washington Academy of Sciences, American Water Works Association, and Delta Tau Delta fraternity.

In the 25 years of his service in the Geological Survey he made many valuable contributions to the geology and hydrology of the United States and he deserves much of the credit for the success of the Ground-Water Division and the development of methods in the investigation of ground-water. His first work in the Geological Survey was his watering-place survey of the Mohave Desert Region, which resulted in his comprehensive and well-known water-supply paper on the geography,

geology, and hydrology of that region. His next major achievement was his intensive study of the ground-water resources of New Jersey, in cooperation with the State Geological Survey, from 1923 to 1928. Here he pioneered in the use of automatic water-stage recorders on observation-wells and made the first critical studies of the continuous records thus obtained--a technique which has proved to be immensely valuable in ground-water studies. Here he also developed the rating-curve method for determining safe yield under conduit conditions and the pumping method for investigating salt-water encroachment. Later he became the outstanding authority on the ground-water hydrology of other parts of the Coastal Plain, notably Long Island, North Carolina, Florida, and the Grand Prairie Region of Arkansas. His last major field-work was in the Mill Creek Valley, Ohio, in which his birthplace is located.

Mr. Thompson accepted the Chairmanship of the Committee on Underground Water when the original nine permanent Research-Committees were organized in the Section of Hydrology in 1931, and he continued to render faithful and effective service in that capacity until June 30, 1942, as is shown by the comprehensive, constructive, and cooperative character of his 11 annual reports and by the large number of ground-water papers that were presented and published during the four tri-

David Grosh Thompson
1888-1943

ennial terms during which he served.

He was one of the leading authorities on the legal regulation of ground-water supplies and made notably constructive and practical contributions to the solution of the perplexing problems relating to such control. In 1939 a paper on this subject, of which he was the senior author, was awarded the Goodell Prize of the American Water Works Association. This Prize is awarded annually to the member who has made the most notable contribution to the science or practice of water-works development.

Many of the members of the Ground-Water Division received their first training under Mr. Thompson, and many others have profited by his criticisms and suggestions. By this unobtrusive service he contributed immeasurably to the morale and technical work of the Division, as is shown by the following statement furnished by S. W. LOHMAN:

> "I first met Mr. Thompson in 1930 at Sunbury, Pennsylvania, where he came to spend about two days with me going over the progress of my work in northeastern Pennsylvania. I liked him from the start. I had the pleasure of working under his supervision on two other projects--Elizabeth City, North Carolina, in 1932, and the beginning of the Witchita, Kansas, investigation in 1937.

"Of the many good qualities possessed by Mr. Thompson may be mentioned his kindness and helpfulness to others. When he took me to Elizabeth City he related to me every shred of information or advice that he thought would be helpful to me, and nearly all of it did prove helpful. His assistance did not terminate when he returned to Washington, for he kept on digging out maps, reports, data, etc., and sent them down to me with detailed explanatory letters. Although some of the letters were long, I soon learned that I could well afford to read every word carefully and that everything he had to say was sincere and helpful. Back in the Washington office Mr. Thompson was always glad to help anyone on any problem at any time."

Perhaps his greatest achievement was the vast amount of extremely valuable work that he did in the present emergency on the water-supplies for military and naval establishments and war industries. In the first world war he was denied the opportunity to serve in the armed forces because he was needed for civilian work on water-supplies for war purposes. On account of this experience and his great familiarity with the geology and hydrology of all parts of the country, he took the leadership in the service of the Water Resources Branch in advising on water-supplies for many hundreds of war projects, and to the day of his final illness he worked on these projects with great intensity and effectiveness.

Mr. Thompson had the research type of mind. He had a keen interest in a wide range of scientific problems and especially in new problems. His investigations were deep and thorough. Unfortunately he kept himself always overloaded with work, but his scientific product was large and of high quality.

He was a man of sterling character--clean, upright, wholly without guile, devoted and kind to his family, considerate and unselfish in all his human relations. Utterly honest and independent in the expression of his views, he often disagreed vigorously with his coworkers in regard to both technical problems and questions of policy. But these differences were wholly impersonal and without animosity on his part. Hence, he was esteemed and loved by a wide circle of friends and professional associates. A member of the Methodist Church, he seldom spoke about religion, but his whole life reflected a reverent and Christ-like spirit.

RICHARD CARLYSLE CADY

O. E. Meinzer

Major RICHARD CARLYSLE CADY died January 15, 1943, at the age of 35 years, as a result of accidental injuries received on January 3, while on duty overseas in the United States Army. He had been engaged for about a year in locating well-sites to develop water-supplies for military establishments in Africa and Asia. He was buried with full military honors in a British military cemetery in Africa. He leaves a wife, Mrs. Beatrice Dunn Cady, two sons--Richard, Jr., and James, aged 8 and 5, respectively--and his parents, Dr. and Mrs. James D. Cady.

Major Cady was born in Cortland, New York, August 7, 1907, graduated from Colgate University, and did postgraduate work in Colgate and Harvard. He was appointed in the Geological Survey, United States Department of the Interior, in 1930, and from 1931 until he began his work in Africa he served continuously in the Ground-Water Division of the Geological Survey. He was a member of the American Geophysical Union, the Society of Economic Geologists, the Geological Society of Washington, and the Sigma Gamma Epsilon and Phi Gamma Delta fraternities.

Major Cady is the author of a number of papers relating to geology, hydrology, and meteorology. It is believed that when his two comprehensive reports on western Nebraska are published it will become evident that he has made a notable contribution to the geomorphology, Tertiary and Pleistocene geology, and hydrology of the Great Plains. Thus, his untimely death is a serious loss to these fields of science.

Dick Cady enjoyed life and lived it fully. He had a well-developed sense of humor. He had many friends and spent much time with them, and yet he found time to read widely, enjoy good music, live a very happy family life, and write creditable poetry. He was a philosopher and idealist. His thinking was characterized by broad interests and perspective, and by deep sympathy with the underprivileged.

The meager information that has penetrated the veil of secrecy indicates that his work overseas was successful and has had valuable military results. This is also indicated by his promotion from the rank of Captain to that of Major. His entrance into the Army for the dangerous work

Richard Carlysle Cady
1907-1943

in Africa was entirely in accordance with his enthusiastic and patriotic desire to serve the country in this critical time by application of the special skill that he acquired in his years of ground-water investigation. Since his death his wife has remarked that even if he had known the outcome, he would have gone just the same.

MAX HARRISON DEMOREST

François E. Matthes

Of glacial geologists the United States has produced a goodly number during the past seven or eight decades, but of glaciologists--students of living glaciers and glacier-ice--this country has at no time possessed more than a scanty few. It is therefore a particularly grievous blow to American science that of the handful of glaciologists of the present time we should have lost through the death of MAX HARRISON DEMOREST one of the most brilliant and, even in his youth, most outstanding.

From the meager advices given out by the War Department it appears that Demorest, who was commissioned a First Lieutenant in the Army Air Corps and was stationed at a remote outpost in Greenland, lost his life on November 30, 1942, in an accident with a motor-sled. We may derive some slight satisfaction from the knowledge that he did not fall before a brutal foe, but met death while on an errand of mercy in a brave attempt to rescue the crew of an army plane that had been forced down on the inhospitable ice-sheet. Of the nature of the accident, no details have been divulged.

Max Demorest was born on February 18, 1910, at Flint, Michigan, where his parents, Mr. and Mrs. Harry Demorest, still reside. Growing up in an environment that everywhere bore the marks of large-scale glaciation, he early developed an intense interest in the study of glaciers and ice-sheets, and so, in 1930, while still a young student at the University of Michigan he eagerly

embraced the opportunity offered him to serve as assistant meteorologist and aerologist on the Fourth Greenland Expedition sponsored by the University. In 1932 and 1933, again, he accompanied the Pan-American Airways Greenland Expedition as glaciologist and assistant meteorologist, and thus, with his mind ever alert for glaciologic and meteorologic phenomena, he gained during those long sojourns in Greenland a remarkably clear insight into the characteristics of the great ice-sheet and the climatic conditions that control its existence. Some of the observations which he made and the ideas which he formulated on those expeditions he embodied in his first scientific paper, that on the "Glaciation of the Upper Nugssuak Peninsula, West Greenland." Though he wrote it at the age of 25, anyone versed in arctic literature might readily believe that paper to be the product of a mature glaciologist. In it Demorest first announced his conception of the basic law of motion in ice-sheets--the most baffling problem in all glaciology.

"The ice moves out", he wrote, "radially from below the centers of greatest accumulation, the rate of movement in the various directions being dependent on the different pressure-gradients. As the ice is forced out from beneath these centers of accumulation, the higher ice moves down to take its place." No physicist acquainted with the characteristics of ice-sheets and the properties of glacier-ice will for a moment doubt the soundness of that law.

Max Harrison Demorest
1910-1942

In 1934 Demorest went to the University of Cincinnati to teach and study, and there in 1936 he received the degree of Master of Science. Next he went to Princeton, which school in 1938 conferred upon him the degree of Doctor of Philosophy. For a year he was Assistant Professor of Geology at the University of North Dakota; then, with a grant from the Geological Society of America, he spent a summer studying glaciers in the Canadian Rockies, on Mount Rainier, and in Glacier National Park. His object was to ascertain, as far as might be possible by megascopic and microscopic examinations, to what extent the motion in such glaciers consists of plastic deformation--that is, flowage--and to what extent of shearing movements between rigid masses. That, he realized, was the crucial question.

Only the year before (1938) an epoch-making attempt to solve certain phases of that problem had been made in Switzerland by a group of British scientists working under the leadership of GERALD SELIGMAN, the noted authority on mountain-snow and firn (névé). Working in a cold laboratory hewn in a stationary ice-apron at the head of the Aletsch Glacier, they had applied the technique of optical crystallography to the microscopic examination of thin sections cut from firn and glacier-ice in different stages of development, and thus they had been led to conclude that the porous, fine-grained firn is transformed into the tight, coarsely crystalline glacier-ice, not by mere compaction and the freezing of interstitial melt-water, but by recrystallization under the

dynamic influence of deformational stresses. The changes produced in the crystal-fabric by flowage are akin to those produced in rocks by dynamic metamorphism, involving a reorientation of the crystal-axes with respect to the direction of the stresses.

That revelation, however, was based on only a small number of observations and demanded verification. Demorest decided to undertake such verification and, not relying on field-evidence alone, decided to subject appropriate specimens of glacier-ice to deformation under controlled conditions in the laboratory. He therefore shipped selected pieces of ice from the glaciers on Mount Rainier, packed in solid carbon-dioxide, to New Haven, Connecticut, where suitable arrangements were made for a research laboratory in a cold-storage plant.

Accepting a Sterling Fellowship from Yale University, he was able to devote part of a winter to this extremely difficult and unprecedented type of research, designing in the first place the pressure-apparatus and the specially adapted polarizing microscope required for the tests. The outlay for this equipment was met by a second grant from the Geological Society of America. Further grants from that organization together with a National Research Council Fellowship enabled him to continue the work through 1940 and 1941. Long hours spent in the chilly cold-storage plant at one time threatened to injure his health. Often, instead of trying to set down his notes with his benumbed hands, he telephoned them to his wife, who recorded them at home. During the school-term 1941-42, while teaching geology at Wesleyan University, he traveled back and forth between Middletown and New Haven to carry on his research.

Success eventually crowned his labors. Not only was he able to prove that under deformational stresses the crystal-axes become reoriented so as to give the ice greater plasticity, but he contrived to record on motion-film the process of molecular readjustment as it takes place in the crystal lattices. That remarkable film he displayed in 1941 before the Section of Tectonophysics of the American Geophysical Union.

Unfortunately, circumstances did not permit him to carry his research to completion nor to publish the results of it in full. Only abstracts of his reports to the American Geophysical Union and the Geological Society of America are at hand, but the very precision of the terms in which these are couched affords a clear index of his achievements. By the war, suddenly, his research was brought to a halt. Inevitably, because of his intimate knowledge of glacial and climatic conditions in Greenland, he was called upon for service with the Army Air Corps in that arctic country. Obliged to resign a Guggenheim Fellowship that would have enabled him to continue his studies for another year, he went willingly to give our fighting forces the benefit of his special attainments.

Demorest nevertheless has left to glaciology a priceless legacy. Fully convinced by his experimental research, as well as his field-observations (set forth in "Ice flowage revealed by glacial striae"), that under slowly acting differential stresses glacier-ice yields like a plastic substance, he expounded categorically his conception of the laws of glacier-motion--the conception that he had announced in a preliminary way on his return from his earlier visits to Greenland. The first expanded statement was contained in his paper on "Glacier regimens and ice movement within glaciers", which formed Part I of the study on "Glacier thinning during deglaciation", published jointly by RICHARD FOSTER FLINT and himself. The second and most complete exposition he gave in his paper on "Ice sheets", which has recently been published posthumously by the Geological Society of America.

In these papers he outlined deductively the mechanics of two distinct modes of ice-flow--direct gravity-flow, such as occurs typically in valley-glaciers descending moderately steep gradients, and extrusion-flow, such as is characteristic of ice-caps and ice-sheets, being induced by differential pressures within those masses. In direct gravity-flow the rate of movement increases differentially from the frictionally retarded bottom layers up to the surface; in extrusion-flow, on the other hand, the more plastic lower layers are squeezed out, in spite of friction, from beneath the load of less plastic upper layers, gravity acting as an indirect agent. Both types of movement had been noted by previous observers, but never had they been explained in terms consistent with the laws of plastic mechanics.

Demorest at the same time was not oblivious of the fact that differential movements sharply localized along narrow zones, or planes, in the ice, and closely akin to shearing, or faulting, normally occur in all glaciers and ice-sheets. Such shear-planes, particularly abundant near the terminus and the margins of glaciers, often have been pointed to as presumptive evidence that glacier-motion consists primarily of shearing movements and only secondarily of plastic deformation. Demorest offered the first rational explanation of the manner in which the two contrasting types of movement are related to each other, and that, unquestionably, is his supreme contribution

to glaciology. He showed that, though glacier-ice is capable of plastic deformation under slowly applied forces, any abrupt stoppage of its normal gravitational flow by an obstructing mass, whether composed of slower-moving, or wholly stagnant ice, tends to give rise to shearing and overriding movements. He thus added to glacier-mechanics the important concepts of obstructed gravity-flow and obstructed extrusion-flow, and thereby provided the key to a baffling problem that has been the subject of controversy between opposing schools of thought for more than a hundred years--ever since the pioneer days of AGASSIZ, TYNDALL, and FORBES.

This appraisal of Demorest's contribution to glaciology may be of special interest to the membership of the American Geophysical Union for the reason that glaciology is one of the subjects that are included in the scope of the Union's program of research. When the Section of Hydrology was formed, it was realized that the study of glaciers and ice-sheets as masses of crystalline water-substance stored on the lands of the Earth is distinctly within the province of hydrology, and accordingly provision was made for their study from that angle by a permanent Committee on Glaciers. On that Committee, Demorest occupied a unique place by reason of the unusual line of research to which he had dedicated himself. It need hardly be added that his passing is felt to be a serious, if not irreparable, loss by all the members of the Committee.

Demorest's interests, however, were not confined to glaciology alone, but embraced also related problems in glacial geology and meteorology. His writings in these two fields, dealing as they do with knotty, controversial questions, merit attention both for the extraordinary clarity of thought and the calm, judicial temper which they reveal. One could not quarrel with such a man.

Recognition from the scientific world came quickly to Demorest. In 1940 he was invited to serve on the International Commission of Snow and Glaciers. In 1942 acceptance of his laws of glacier-motion was indicated by their incorporation into the chapter on "Glaciers" in the National Research Council's volume on "Hydrology" [No. 9 of the Physics of the Earth series], and in the same year he was nominated for fellowship in the Geological Society of America. Demorest died before the date of his election, but the Council of the Society honored him by regarding him nevertheless as having been elected.

He is survived by his wife, Rebecca Humphreys Demorest, and their young daughter. To them, to his parents, and to his numerous friends the sense of personal loss may be compensated somewhat by the assurance that, though he reached the age of only 32, his name is writ large on the rolls of science. The silent ice-sheet of Greenland, which he studied with such absorbing interest, is his appropriate shrine.

Note: Since the above memorial was written, the whole chapter of successive disasters, incredible hardships, and daring attempts to rescue, through five months of a Greenland winter, in which Demorest and several others lost their lives, has become known in all its harrowing details. Early in May 1942 the survivors reached Washington and their account was published in the press. From that account the following facts are culled:

On November 9, 1942, a flying fortress piloted by Captain ARMAND L. MONTEVERDE crashed in a storm on the ice-cap of Greenland. The ship broke in two, with the tail across a crevasse in the ice, but the crew managed to make a shelter for themselves in the fuselage. One had a broken arm and frozen hands, and another had frozen feet. The radio was damaged but they succeeded in repairing it and contacting their base. Stormy weather prevented any attempts at rescue until November 24--15 days after the crash--when Colonel BERNT BALCHEN flew a transport plane to the spot and dropped supplies, fuel, and arctic clothing.

The wrecked plane having been located, Lieutenant MAX DEMOREST and Staff Sergeant DON T. TETLEY, who were stationed at an outpost about 25 miles from the plane, set out on November 29 with two motor-sleds, each leading a tow-sled. They were obliged to travel in roundabout ways in order to avoid crevasses. Their progress was slow, not merely on that account, but because, for safety, Demorest, who was the more experienced of the two in arctic travel, skied ahead to test the snow, while Tetley brought up first one pair of sleds and then skied back to bring up the other pair.

The arctic night soon overtook them, but, the sky being clear, they were able to proceed with flashlights. In one place the snow-crust gave way under a sled, but they managed to pull it out. Thus they continued laboriously until they were stopped by a maze of crevasses, a little over a mile from the flying fortress. The men there were expecting them and sent up flares to guide them. Leaving the sleds, Demorest and Tetley felt their way along on skis and, about midnight, reached the plane. They found all awake and a chicken dinner waiting for them. Demorest, making

the most of his previous experience in the arctic, examined the injured men and put new dressings on their frozen and frost-bitten members.

About one o'clock in the morning (November 30) Demorest and Tetley returned to their sleds following their ski-tracks back. They then resumed the journey with the sleds, Demorest leading with the first pair. All went well until they were within a hundred yards of the wrecked plane. There Demorest turned off, describing a wide circle in order to head the sleds in the right direction for the return trip, it being difficult to turn the sleds around after they were once frozen in the snow. He had gone but a few yards when, without warning, he suddenly crashed through and disappeared, sleds and all, into the depths of a crevasse. The crew of the plane came with ropes, but the sleds were so far down that they could not be reached. Not enough rope was at hand for the making of a rope-ladder, and radio calls for a rope-ladder brought in return instructions not to attempt to go down into the crevasse. All that the men could do, therefore, was to call and watch for possible signs of life. But they watched in vain and finally gave up hope. Demorest had been claimed by the Greenland ice-sheet, which he loved and understood better than many another arctic explorer.

The other attempts to save the fliers, the tragedies that followed, and the final rescue of Captain Armand and the remainder of his crew by Colonel Balchen on April 6, 148 days after the crash of the flying fortress, cannot be recounted here. Together they make a story of sustained fortitude and boldest daring that will stand forever as an epic in the annals of the Army Air Corps.

CONFERENCE ON THE PRESENT TENTATIVE PROGRAM OF THE COMMISSION ON CONTINENTAL AND OCEANIC STRUCTURE OF THE INTERNATIONAL UNION OF GEODESY AND GEOPHYSICS

INTRODUCTION

R. M. Field, Chairman of the Commission

The Commission welcomes this opportunity to discuss with the American Committee of the International Union of Geodesy and Geophysics a tentative program in international geoscience. Our principal desire is to help keep the International Union of Geodesy and Geophysics alive--not merely in cold storage--until its whole membership can again unite in the support of world-science for post-war problems. We also feel that our endeavors, at this time, may be of interest to other international scientific unions, which, for several reasons, have entirely ceased to function or even to maintain contacts between their personnel in the allied countries.

The International Commission on Continental and Oceanic Structure was appointed, as most of you will recall, at the Edinburgh Assembly (1936) of the International Union of Geodesy and Geophysics with the instructions that it seek to stimulate and facilitate the accumulation and correlation of factual information: First, as to the nature of the crustal structures characteristic of continental and oceanic areas; and second, as to the nature of the terrestrial processes responsible for the recurrence of certain crustal structures and patterns over the entire Earth's surface.

The war is seriously interfering with the work of the Commission in many ways, but the war has also increased, rather than diminished, the responsibilities of the Commission for carrying forward its appointed tasks as diligently and successfully as possible.

The International Commission, as originally appointed, consisted of the following men: R. M. Field (Chairman); J. A. Fleming (Secretary); G. Angenheister; B. Helland-Hansen; O. T. Jones; Harold Jeffreys; F. A. Vening Meinesz. Its function was, in essence, to be the extension into the international field of the work of the various national special committees engaged in the study of continental and ocean-basin areas.

The Commission presented a printed report and held open meetings during the Assembly of the International Union of Geodesy and Geophysics held in Washington (September, 1939). At this last meeting of the International Union, it was voted that all officers of the International Union should continue in office until the next international assembly.

It is therefore obvious that certain members of the Commission cannot, at present, take active part in the work of the Commission, but steps are being taken to select suitable alternates who will act for these members until they are able to resume their responsibilities.

But let us turn now to the five projects upon which the Commission is now tentatively concentrating its attention and energies.

Project I aims at the collection of more data regarding variations in gravity which often form distinct patterns that are particularly characteristic of regions of mountain-building where the deformed sedimentary and associated igneous intrusives are distinctly arc-like in character. These peculiarities in the variations of gravity occur both where chains of islands rising from the floor of the ocean assume a circular alignment familiarly known as island-arcs, and where mountain ranges in the form of crescents occur both within the continents and along certain continental margins.

This project for the present may consist of a continuation on land of the marine measurements of gravity recently carried on by the exploration of Meinesz and his collaborators--explorations which have resulted, as you know, in the discovery of strips of gravity-deficiencies or negative anomalies in the island-arc areas. This discovery has been of utmost importance to our knowledge of the composition and structure of the lithosphere, and to our understanding of the ways in which the crust has been deformed.

In order eventually to carry out this project, we should begin to plan the establishment of primary pendulum-gravity stations at proper intervals throughout the Cordilleran and foot-hills regions of North and South America, and at strategic points in the "exposed-shield" and "covered-shield" areas of the two continents. As soon as practicable (and perhaps fairly soon) this program should be extended into other parts of the world--with the ultimate hope of obtaining a complete net of primary gravity-stations on something like a 100-km spacing, amplified by second-order (gravimetric) stations spaced at approximately ten km.

Of equal importance in this international correlative geophysical-geological research, if only in the Western Hemisphere, are radioactive-age determinations of igneous rocks. Such determinations, according to the Committee of Measurement of Geologic Time, of the Division of Geology and Geography, National Research Council, are particularly needed from such geographically diverse localities as Wales (England), the Alps (Switzerland), Karroo (South Africa), Grand Canyon (Arizona), the Appalachians, northwest Highlands of Scotland, Jurassic granites of Japan, the Sinian of China, the Front Range and Beltian of the Rocky Mountains, etc. With the further exploration of island-arcs, ADAMS and HESS have emphasized the relative importance of the radioactive ultra basics, such as peridotites and serpentines, in the dating and migratory movements of orogenics. Because of the unique and immediate relationship of peridotites to mountain building, their age-determinations are much more precise in the comparative chronology of tectonics in widely separated regions than are the age-determinations of granite or other igneous rocks.

Project II looks toward the further collection and correlation of data on the geographic occurrence, structural relationships, and dynamic significance of intermediate and deep-focus earthquakes. Like the discovery of the existence of "negative-anomaly strips"--the recognition of the occurrence of deep-focus earthquakes and the recently made compilations showing their geographic distribution and obvious genetic relationship to mountain-building and island-arc formation have suggested a new field of cooperative research in which men of all lands can join to great mutual advantage--currently in the sphere of basic research, and ultimately in the development of new geoexploratory arts and methods. Captain N. H. HECK, President of the International Association of Seismology, has pointed out the necessary distinction between intermediate and deep-focus earthquakes since, especially in South America, their loci are not the same. Thus any additional seismic stations should be located with this fact in view. We should try to discover why western North American has no deep-focus earthquakes and few intermediate, except in Central America, any why the regions without either deep or intermediate shocks have no adjacent deep ocean-troughs.

Here we have an excellent example of the need for advanced careful deliberation and planning for any future international seismological program. Each nation can do its share, provided that it is already acquainted with the international requirements for the progress of seismology as a whole, and especially in its relations to other branches of geoscience.

Project III, as now outlined, is aimed at the gravitational, petrological, and structural study of the Earth's older orogenic and volcanic zones, which are marked by relict zones of negative anomalies and by groupings of old volcanic centers which were apparently developed over considerable periods of time and according to quite definite space- and time-controls. Moreover, it is to be remembered that these older orogenic and volcanic zones are featured by the presence of many ore-deposits which have probably been concentrated and localized according to the operation

of fairly definite geological, geochemical, and structural laws--laws such as are still controlling the structural and volcanic development of the world's modern seismo-tectonic-volcanic belts.

Project IV is directed toward the study of the topography and structure of the floors and basins of the ocean. The techniques and general procedures needed for this project have already been largely developed in the sonic ranging and mapping of continental-shelf and submarine-canyon areas, in the magnetic oceanic surveys, in the seismic and gravitational study of continental-margin areas, and in the core-sampling of the sediments which mantle the floor of the ocean. The need for magnetic surveys, especially at sea, had become acute even before the war. Entirely aside from the immediate practical importance of these surveys--when an adequate theory can be developed to account for the remarkable changes in the isoporic foci in and east of South Africa--we will have added a new and most important technique to our net of correlative methods for studying the sub-oceanic lithosphere.

However, we know that, just as the pre-war marine geophysics has had a great influence in the development of new destructive gadgets, so the knowledge gained in the improvement of these destructive gadgets will greatly accelerate the marine geophysical exploration after the war. I predict that it will be in this field (exploration of oceanic basins) that we will see the most important and most rapid advance in fundamental geoscience. At the instigation of the Commission in 1938, the British Navy, with the cooperation of the Royal Society, the Geological Society of London, H. M. Geological Survey, and the Department of Geodesy and Geophysics of Cambridge, formed a National Committee for the Geophysical Exploration of Oceanic Areas. An important project for the mapping of portions of the Atlantic Ridge was planned with the help of the United States Coast and Geodetic Survey. Only the war temporarily stopped this most important project, but those who have had experience with oceanic geophysics are fully aware of the very limited technical personnel. No other field in geoscience will offer such great opportunities for post-war geophysicists as this. Also, with the possible exception of meteorology, no other field requires such long-time careful cooperative planning from the international point of view.

Project V concerns the integration of regional structural data, such as reported by A. W. JOLLIFFE in Transactions of the American Geophysical Union for 1942 and such as have been incorporated in the Tectonic Map of the United States (prepared by the Tectonics Committee of the National Research Council, and now being published by the American Association of Petroleum Geologists), and in Special Exhibit 1, prepared by the American Geophysical Union's Special Committee on Continents for the Washington Assembly of the International Union in 1939. It is in this field of research that aerial photographs are of supreme importance to the geologist, as well as to the geographer, and plans should be prepared for an international catalog of the Western Hemisphere.

The structural features and patterns characteristic of the Canadian Shield, Mississippi Valley Region, and Gulf Coast, are undoubtedly duplicated in many other parts of the world. Also, a compilation of the structural patterns of the "uncovered-shield" regions of Canada will be of great scientific and economic interest, both to the men engaged in the exploration of the "covered-shield" area of the United States and to the men engaged in the mapping and exploration of other "covered" and "uncovered-shield" regions, as for example, those of Guiana and Brazil.

In concluding the introduction to this Conference on the tentative program of the Commission, may I repeat an earlier paragraph: "The war is necessarily interfering with the work of the Commission in many ways, but the war has also increased rather than diminished the responsibilities of the Commission for carrying forward its appointed tasks as diligently and successfully as possible." The complete role of science in human affairs must, at all times, include the maximum on constructive planning even during those particularly difficult periods when much of its effort is expended in the destructive techniques of war.

We may not only begin to plan these fundamental correlative studies in geoscience now, we can also arrange to do at least some of them in the Western Hemisphere. Individuals and agencies are available, if not always the same that have been active in the past. If certain economic and political scientists are devoting their entire time and energies to international problems, so may certain geophysicists and geologists to the equal benefit of human affairs. The Commission has the advantage, however, that its present objectives are entirely limited to those fundamentals in geoscience which are of equal benefit to all regardless of their current competitive political and economic theories or plans. We American geophysicists would not be meeting in Washington this spring if we did not believe this to be true.

Princeton University,
Princeton, New Jersey

REMARKS BY DELEGATES OF EACH SECTION AND GENERAL DISCUSSION ON COMMISSION'S FIELD IN INTERNATIONAL RESEARCH IN THE WESTERN HEMISPHERE, ALLIED COUNTRIES, OR ELSEWHERE

W. D. LAMBERT (Section of Geodesy)--I hold no office in the Section of Geodesy. The President and the Secretary of the Section are both here to speak for the Section, if they so desire. I think I may say, however, that the Section of Geodesy has been able to do little in the way of pure science. Most of us have had our attention turned to problems in some way connected with the war, or because of the war we have had to take on extra work of routine character.

There has been, however, one interesting geodetic development of both practical and scientific interest. The various oil companies have developed very accurate and very sensitive gravimeters and, best of all, gravimeters that can be operated both easily and quickly. The accuracy obtainable is of about the order of 0.01 milligal. The gravimeter-record of the rise and fall of gravity under the influence of tidal forces is about as clear and regular as the record of a tide-gage recording the rise and fall of the water-tide in a harbor. To interpret the gravimeter-records for geophysical prospecting and to get the mean value of gravity at a point, a correction for tidal effects must be applied.

To make a really scientific reduction of precise leveling, we need the values of gravity along the line of levels. For want of anything better we have hitherto used the theoretical values of gravity. Now it becomes practicable to use observed values--a great improvement in certain cases. I imagine that a gravimeter could be operated along with a leveling party and could cover the country at a comparable speed.

The gravimeters give only relative gravity and must be checked by observations at points where gravity is known. This would mean frequent pendulum-stations. If means are available, I think that the return of peace will bring a great development of gravimetric work.

It will be of interest also to study the tidal variation in gravity at a number of strategically chosen points by getting gravimetric records there over a period of days, weeks, or months. These records should teach us something about the elastic properties of the Earth as a whole and perhaps something about local peculiarities in the geological structure, though in the matter of local structural peculiarities, I foresee difficulties of interpretation.

O. W. SWAINSON (Section of Seismology)--Seismology's contribution to the study of continental and oceanic structure, and especially to Project IV of the Commission, consists largely in collecting data on seismic waves which traverse the Earth's surface. It is through the variation in the speed of these waves that we can make certain limited deductions regarding crustal structure along the paths traversed. While it is possible to make rather detailed study of continental structure through geophysical and seismic surveys, our information regarding oceanic structure is limited almost entirely to the study of seismic surface-waves recorded at stations on continents and islands.

The Commission will be gratified to know that, in the Atlantic Basin, the Milne-Shaw seismographs installed in Bermuda under the sponsorship of the International Commission are still in operation in spite of certain handicaps imposed by the war. They are being operated by the Meteorological Office of the Government of Bermuda, and the records are being interpreted by the United States Coast and Geodetic Survey.

In a similar way the Danish stations in Greenland at Scoresbysund and Ivigtut are being maintained through the cooperation of the temporary Government of Greenland, the Department of State, the Commission on Continental and Oceanic Structure and the Association of Seismology of the International Union of Geodesy and Geophysics, the American Philosophical Society, and the United States Coast and Geodetic Survey. Dr. R. M. FIELD, Chairman of the Commission, has played an active part in making the continuity of the records possible. The war has made it impossible for the Coast and Geodetic Survey to study these problems as it desires, but some conclusions have been reached as set forth by R. R. BODLE of that Survey in the recent meeting of the Section of Seismology of the American Geophysical Union. While the seismograph-records are undoubtedly affected by conditions at the place of origin, there is little doubt that the Atlantic Basin is traversed by high-speed surface-waves just as in the case of the Pacific. An eminent seismologist has maintained that modified continental layers exist in the Atlantic Ocean but the recent observations indicate that if the layers exist they are very thin. The important part is that it has been possible to maintain the essential seismological stations, as a matter of this kind can only be settled by a large amount of data.

C. W. THORNTHWAITE (Section of Meteorology)--I had a communication from the Chairman of the Committee on Meetings which asked me to select a delegate who would be prepared to state what consideration the Section of Meteorology had given or is planning to give to international research in the Western Hemisphere, allied countries, or elsewhere, particularly along the general lines of the field of this Commission. I was not fully acquainted with the work of this Commission, and consequently I did not think that the Section of Meteorology was doing anything that would have anything to do with the research on continental and oceanic structure. Therefore, I did not appoint a delegate and there is no representative here to make a report at this time.

R. M. FIELD--Perhaps the instructions to the Commission at Edinburgh in 1936 were too broad. Briefly these instructions may be summarized as follows: (1) Nature and causes of regional magnetic patterns and anomalies; (2) nature, distribution, and dynamic causes of regional and gravitational anomalies; (3) nature and causes of regional and temporary variations in radio transmission and reception; (4) nature and dynamic causes of crustal deformation-patterns such as may control regional occurrence or non-occurrence of valuable mineral resources; (5) relation between possible cosmic cycles or rhythms and possible prediction of long-period rhythms as affecting climate and weather; (6) relations of relative climate, hydrology, and soils.

H. F. JOHNSTON (Section of Terrestrial Magnetism and Electricity)--Dr. ECKHARDT presided yesterday at the meeting of our Section and stated that he had been out of the city and had no opportunity or time to appoint a delegate from the Section. Unfortunately also, urgent defense problems made it necessary for him to leave during the meeting of the Section and he could not hold a contemplated discussion with Dr. Field.

H. A. MARMER (Section of Oceanography)--The problems with which the Commission is concerned do not appear to be distinctly oceanographic problems but are related unquestionably to oceanography. There is one oceanographic problem in which I think the Commission might be interested. Through the opportunities afforded by the program of inter-American cooperation, a number of stations for recording of tides have been installed on the west coast of South America all the way from the Straits of Magellan to the northern part of the coast and series are being derived that will permit a determination of what the relative elevations of land and sea are doing. There are not many places where one may be sure what changes relative to land are taking place. Unless the observations are continued, one would not know what has been happening to the sea or to the land. Without continuous observations of tides, data are lacking from which precise conclusions may be drawn. The program along the west coast of South America, started about two years ago, offers an unusually fine opportunity for international, or at least inter-American, study of this problem.

W. T. THOM, JR.--The new tidal stations on the west coast of South America, just mentioned, seem to come as particularly timely and important additions to the world's bench-mark systems, because notable movements of uplift and depression may be in progress along different parts of this coast in consequence of the continuing uplift of the Andean ranges, accompanied by a corresponding depression of the Atacama Foredeep and of some littoral areas.

The new tidal stations will give us exact and dated information as to such movements as may now be in progress along this coast, and, taken in conjunction with other sorts of geophysical and geological evidence, should shed much light on the crustal forces and processes involved in the building of this part of the rim of the Pacific Basin.

J. F. SCHAIRER (Section of Volcanology)--President BUDDINGTON of the Section of Volcanology appointed me as a representative, presumably because I happen to be Vice-President of the Section, and Dr. Zies because he is one who is most familiar with the activities in volcanology. I will call upon Dr. Zies to comment on the Commission's program.

E. G. ZIES (Section of Volcanology)--Dr. Field's program as outlined under Project III specifically calls attention to the desirability of making a gravitational, petrological, and structural study of the Earth's older orogenic and volcanic zones. We should include a cooperative study of active and dormant volcanic zones. The correlation of the data will surely yield fruitful results. Judd in his book on "Volcanoes" makes the statement: "The power of prediction is alike the crucial test and crowning triumph of scientific theory." Many of our active and dormant volcanoes are located in or near densely populated areas. The ability to predict an eruption has consciously or unconsciously been the goal of most volcanologists. The hope has been entertained that if this were possible we should be able at least to mitigate the suffering that often is the aftermath of an eruption. At present our knowledge is so scanty that on psychological grounds it is just about as dangerous to make a prediction of activity that does not eventuate as it is to fail to predict activity

that suddenly overwhelms the countryside. The scantiness of our knowledge is largely due to the fact that we have been too intent upon studying the purely surface-phenomena. We too often overlook the fact that an eruption is the culmination of a series of events that for a long time have been brewing beneath the surface and hence can not be directly observed.

Geophysical methods of investigation have now reached a stage of development that should encourage us at least to try them out and learn to what extent they can be used in studying the forces that are at work beneath the surface. Such studies of the physical aspect of the problem also involve more detailed geological investigations of the volcanic area together with mineralogical and chemical study of the products brought to the surface. These few statements suffice to indicate the magnitude of the problem and the necessity for cooperative study.

An active volcano has a cold exterior and a hot interior. When it is dormant the hot igneous material in what may be called the hearth of the volcano is undergoing a series of changes that eventually may lead to an eruption. Can these differences in energy-levels be made perceptible by geophysical methods? We certainly at present can not answer this question. A study of variations in gravity may furnish a clue provided that the differences in density are not too small to be measured by the methods now in use. Volcanic areas are intimately associated with areas in which mountain-building forces are at work. The desirability of studying variations in gravity in the latter areas is recognized. The more detailed study that will be required for the former could be fitted into the general program of work.

Volcanic areas are also areas of seismic activity. Is the movement of the hot igneous material from the interior towards the surface accompanied by characteristic tremors? A study of the local tremors so often observed in the neighborhood of a volcano may prove of considerable help in forecasting an eruption and may also yield information as to the depth of the hearth. Two, or better three, seismographs strategically located and adapted for recording minor tremors are likely to determine with fair accuracy the focus of the tremors. Such work could be tied in with the larger program involving the study of seismic activity peculiar to the movement of large masses.

Such studies as have been indicated above should be carried out not only in the volcanic areas of the continents but also in the areas of the volcanic islands, especially those of the Pacific Ocean. These islands in many places have an enormous height above the floor of the ocean. Obviously the study of volcanic activity can be fitted into a program involving oceanographic studies.

Magnetic studies of the area in the immediate vicinity of a volcano have been made and the results obtained are sufficiently provocative to encourage one to continue them. There is evidence at hand to indicate that, during a violent explosion, sufficient fine dust is expelled into the upper atmosphere to lower, for a season or two, the average temperature of large areas of the Earth's surface. It seems obvious that a cooperative study of volcanic activity fits into practically every part of Dr. Field's program. Since the purposeful outlook of prediction underlies the studies of volcanic activity, one begins to wonder if such a study could not be used as a provocative guiding thread for the whole program. It would certainly provide the human-interest angle that encourages many scientists to undertake a seemingly hopeless task.

L. G. STRAUB (Section of Hydrology)--The situation is much the same as in volcanology. President CHURCH could not be here and by chance of office I was asked to be a representative. There are, however, two representatives from hydrology who are much more qualified to speak on this subject--Dr. Meinzer and Mr. Matthes.

O. E. MEINZER (Section of Hydrology)--Hydrology comes into this picture mainly through the work on which Mr. F. E. MATTHES is an authority in connection with glaciers. I think there is a very definite relation of the historic and prehistoric fluctuations in glaciation to this problem, and Mr. Matthes has made effective contributions to it. In the field of ground-water I think we touch rather lightly upon it, except incidentally in that a good deal of our work is along the seashore and consequently we may make contributions to problems of eustatic fluctuations of sea-level. The salt-water relations to ground-water are involved in these problems but mostly geology as a sort of by-product. I think the part of hydrology with which Mr. Matthes is especially concerned relates definitely to the problems of continental and oceanic structure.

F. E. MATTHES (Section of Hydrology)--As Dr. Meinzer has indicated, that branch of hydrology which deals with the study of glaciers and ice-sheets has distinct bearing on problems concerned with the structure and the mutual relations of continental masses and oceanic basins. The connection between the two fields of science may at first seem remote, yet it proves to be fairly

intimate when one considers that any profound change in the configuration of an oceanic basin will affect sea-level by an appreciable amount, and consequently will also affect climatic conditions.

If it is postulated that, as the result of diastrophic movements in an ocean-basin, at a certain time in geologic history, sea-level was drawn down some thousands of feet, the question arises at once whether the climatic change produced would have sufficed to bring on glaciation in some parts of the world. And the further question naturally arises, whether the glacial conditions that prevailed during the Pleistocene epoch were perhaps caused by a great lowering of sea-level, or a correspondingly great rise of the continents. These are questions which, it seems to me, must be worked out quantitatively, and the results must be checked against the known facts of glacial geology.

It is to be borne in mind, in this connection, that glacial conditions occurred during the Pleistocene epoch not merely once, but four times in succession, at long intervals. Any one advancing an hypothesis that would ascribe the advent of glacial conditions to a strong lowering of sea-level must therefore be prepared to show that the mechanism operated four times during the Pleistocene epoch.

It may be appropriate here to refer to a specific problem that is distinctly within the scope of the Commission's program--namely, that relating to the mode of origin of the submarine canyons that trench the continental shelves. These canyons, as is well known, are cut to depths as great as 8,000 feet below the present sea-level. Among the earlier hypotheses that were suggested was one to the effect that the canyons might be products of subaerial stream-erosion, having been worn by swift rivers at a time when the sea stood fully 8,000 feet lower relatively to the lands than it does today. That was a legitimate conjecture, but one wonders whether in connection with it any thought was given to the climatic consequences of so great a change in the relative positions of land and sea. It can be shown from glaciologic and climatologic data that a lowering of sea-level of the order of 8,000 feet would have resulted in glaciation of the continents on a vast scale--a scale much larger than any that is known to have occurred during the Pleistocene epoch. A lowering of sea-level, or relative rise of the continents, of about 3,000 feet would probably have sufficed to bring on such glaciation as appears actually to have taken place.

The more purely hydrologic aspects of glaciers and ice-sheets--considering them as masses of water-substance abstracted from the oceans and stored on the lands in the crystalline state--may also prove of interest in connection with the Commission's program. It has been estimated that since the last glacial climax of the Pleistocene epoch enough water has been released by the melting of land-ice to raise the level of the oceans about 300 feet; and it has likewise been estimated that if all the glaciers and ice-sheets now in existence should melt away, sea-level would be raised, approximately, an additional 150 feet. On the other hand, there is abundant evidence that the ice-loads on Scandinavia and North America during Pleistocene times sufficed to depress those parts of the Earth's crust several hundred feet below their present levels; and it stands to reason that the depression of those ice-loaded areas was compensated for by an isostatic rise of surrounding ice-free areas--ocean-basins as well as lands. Both eustatic changes of sea-level and isostatic oscillation of areas of land and sea therefore have occurred in consequence of alternating glaciation and deglaciation of certain parts of continents. Changes of both kinds, though on a relatively small scale, doubtless have taken place even in post-Pleistocene times, first as a result of extensive deglaciation during a prolonged thermic period, and next, as a result of moderate reglaciation during the somewhat cooler historic period.

All changes thus occasioned in the relative levels of land and sea must be reckoned with in connection with problems dealing with the probable effects of crustal warpings, dislocations, or other dynamic events affecting the relations between continents and oceanic basins. They are necessarily interwoven with the Pleistocene and post-Pleistocene histories of continents and oceanic basins, as is already abundantly evident to students of the still controversial coral-reef problem; and it therefore seems not unlikely that glaciologists as well as glacial geologists may be able to contribute something from their side to the projected program of the Commission.

At this point Acting President ADAMS called upon General Secretary FLEMING to take the Chair.

E. INGERSON (Section of Tectonophysics)--Thus far the Section of Tectonophysics has not had any coordinated plans in the field of the Commission. This is due perhaps to the fact that the Section of Tectonophysics is the youngest Section of the Union and that there is no corresponding Section in the International Union. Therefore, there has been no thought given, as yet, to cooperation in these international problems.

There is a further factor, I believe, namely, that no one has as yet defined specifically just what the field of tectonophysics should include. We can get some idea, however, of the scope of the activity of that Section if we consider the membership and program of the Section for the past three years in the fields of geoscience that are not governed specifically by the other branches of the Union. If we take those factors into consideration, it appears that the principal sphere of activity is structural geology, in particular the methods of structural geology that have been intensively developed recently in new techniques in the laboratory and field.

If we take that as a starting point, it is easy to see where such a program can fit in with the suggested activities of this Commission in Project III, particularly the petrological and structural studies of the older orogenic-volcanic zones and studies of their related ore-deposits, and Project V, correlation and integration of structural information on a large scale. Both Projects have very important parts in the suggested program of the Commission. As I have said, we have no coordinated program of participation by the members, but the men affiliated with the Section of Tectonophysics include most of the men in the country who are familiar with these new techniques which can be included in that branch of geology that is known as structural petrology or petrofabrics. These new techniques can and, I hope, will make important contributions to the structural study in at least two different ways: (1) In the more intensive studies of laboratory techniques and studies designed to find out just how minerals behave during deformation from which it will be possible to take the present mineral orientation and determine the direction of motion that produced this orientation and possibly even the direction of the forces involved; (2) intensive field-studies. Those of you who were present at the meeting yesterday afternoon were impressed by the detailed study reported by Professor CLOOS showing how it is possible to make structural interpretation by these methods far more accurate than previous interpretations and I think I can cite examples of interpretations that can be made that are impossible by classical methods. These studies can be made in at least two different ways: (1) Intensive structural studies of areas that have not been studied before, especially areas that previous studies have indicated to be critical for regional interpretations; and (2) restudy or checking of previously studied areas where results have been contradictory or not entirely clear. It is quite possible that many controversial subjects can be cleared up by the application of these new techniques.

J. A. FLEMING--I would like to call attention to the important relations shown by the distribution of the foci of secular change. It is noteworthy that the maximum foci are associated largely with land areas and the minimum foci with oceanic areas; these facts can not but be important in the work of the Commission. Again, we have the distribution and extent of magnetic anomalies, particularly the larger ones, which must be of interest to the Commission. There is also the possible relation between volcanic developments and effects of volcanic activity on geomagnetic conditions.

H. F. JOHNSTON--From the practical end, the Department of State, the War Department, the temporary Government of Greenland, and the Department of Terrestrial Magnetism of the Carnegie Institution of Washington have arranged that the geomagnetic observations at Godhavn, Greenland, be continued and, in addition, that another magnetic station will go into operation early this year so that from the practical side data are being obtained to help with some of the studies of the Commission.

J. A. FLEMING--It may be remarked that some special studies and instrumentation as regards the very short-period fluctuations in geomagnetism are being developed. These and other data being obtained in connection with war work can not for the moment be divulged but they will doubtless be of use in the Commission's program.

C. L. GARNER--The program of gravity-observations that have been made in some of the South American Republics along with the State Department's plan for cultural relations with those countries has been discontinued because of lack of personnel, but it will be resumed at the earliest opportunity. This is a matter which relates to Dr. Field's first recommendation. The more stations we have, the better. Other projects are pending. These are designed to accelerate progress in geodetic control-surveys and in mapping--all essential to the accumulation of geophysical data of importance to the Union.

O. W. SWAINSON--The United States Coast and Geodetic Survey, in cooperation with the South American Republics and the Department of State, is making a magnetic survey of South American Republics. This is a repeat-program which customarily has been made by the Department of Terrestrial Magnetism but which, at this particular time, that organization could not see its way clear to carry out because of other duties and other work that limited its capacity. We have finished observations in Venezuela, Columbia, Ecuador, Bolivia, Peru, Chile, and Uruguay, and a party is at

present in Brazil. The program will continue until June 30, 1943, and, we hope, into next year. Last year we finished a similar program in the Republics around the Caribbean Sea and, as a result, have compiled a new isogonic and isoporic map of that region which is in press at the present time and will be issued soon.

N. H. HECK (President of the International Association of Seismology, read by O. W. Swainson)--It is suggested that, when these projects are studied, further investigation be made to find to what extent several methods should be used in the same region. As an example, in Project II the gravity-observations provided for in Project I are important. It seems to me that a project should be selected in which several lines of geophysical attack may be coordinated. The data obtained in Peru and Colombia by cooperation of the Coast and Geodetic Survey with these countries is a sample of what can be accomplished. It has been decided that this activity was not sufficiently related to the war effort to warrant continuation during the war. It may be said that the activity is a welcomed one, and its resumption after the war seems desirable.

With reference to Project II, there have been some important recent developments in Mexico and in several countries of South America. Installation through the cooperation of Harvard University of an instrument near Pueblo, Mexico, is an important addition. A modern seismograph is being operated at Bogotá, Colombia, and in Chile, though unfortunately without improved instruments. This is important. These stations may help to throw light on the thickness of the crustal layers which has not yet been determined for any part of the Americas south of the United States border.

In Project II distinction should be made between intermediate and deep-focus earthquakes since, especially in South America, their regions are not the same. Any additional seismic stations should be located so as to give the best conditions for determining position and depth of both types of earthquakes. Chile would probably be glad to operate a first-class station, provided instruments and part of operating expenses were furnished. It should be understood that second- and third-class stations refer only to number of instruments and not to their quality and that time-recording should be of uniform accuracy. It seems to me that one aim might be to determine the probable reason why western North America has no deep-focus earthquakes and few intermediate except in Central America and why the region without either deep or intermediate shocks has no adjacent deep ocean-troughs.

The resumption of Project IV after the war requires no new techniques, though some may have become available. The need for magnetic surveys, especially at sea, has become serious. If an adequate theory could be developed to account for the remarkable changes in the isoporic foci in and east of South Africa, it would represent important progress.

I am not sure that Project V is the right place for the suggestion that the photographs from the air obtained by Rich in South America from commercial airplanes should be supplemented by others covering large areas. This is from the viewpoint of geological patterns.

R. M. WILSON--Geography probably can be regarded as a part of geodesy, since geography is used more or less in investigations of other sciences. It is obvious, of course, that the war is bringing together and coordinating a great deal of new geographic information. The Section of Geodesy might easily inaugurate a plan to utilize that information after the war is over if we can find some way to make available to the scientists not only the maps showing the greatly increased detail in geographic knowledge but also the photographs which would be extremely useful directly even before being put into maps. Many photographs have been taken. I presume all of that information will be available after the war for any scientific purposes.

H. ARCTOWSKI--From all that was said so far, I am under the impression that sub-commissions may be formed in order to prepare distinct reports of discussed data, a sub-commission for each of the selected sciences of the International Union of Geodesy and Geophysics. Therefore, geology--geotectonics in particular--will be missing. Such reports, or the six or ten volumes to be published, may not contain the connecting links between different sciences. Such connecting links will not be expressed in form of problems, solved or to be solved, unless an additional volume should be added--a volume of simplifications.

Another plan of work may be opposed to such encyclopedic exposition of our knowledge. In this plan we would proceed by questions. A few examples may be cited.

(1) Consider the Antarctic ice-pack where large fields of ice persist during the winter, simply because of forced displacements due to the winds. Alexander Land is east of us and the main

continent south. [The speaker illustrated his remarks by sketches on the blackboard.] The ice drifting south or east will be compressed. Hummocks are formed. With changes in wind-direction there is drift north towards the open sea. An open water-lane is formed along a hummock. What do we see underneath the hummock? An anti-hummock, an accumulation of ice to a depth of nine or ten meters, upholding the hummock of two or three meters of height above the surface of the ice-field. At four or five meters below the water-level, the ice is very slowly dissolved and, in the course of time, the anti-hummock shows excavations, a tendency towards a spongy structure--a tendency towards a lack of equilibrium. An extensive chain of hummocks looks like an ideal mountain range. Cross-sections of borings with a geological hand-borer show an anti-hummock range. The crest is about two or three meters in front of the crest of hummocks. Besides, the ice-fields differ in thickness. The older ice resists best. The thinner ice has to be broken and pushed beneath. With the advancement of season and an occasional northern drift, we notice frequently gentle ice-foldings in front of hummocks or perhaps a break and a slight downfall beneath sea-level. From now on we have to ask what a geologist has to say. He will answer: Some evident similarity with mountain ranges. And it is evident that from the point of view of such polar-ice observations the topography of many continental regions could be explained simply.

(2) Yesterday, at the meeting of the Section of Oceanography, a most interesting bathymetric chart of the oceans surrounding the Antarctic Continent was shown to us by officers of the Hydrographic Office. A striking tendency of elevation of the bottom of the oceans--surrounding the deep waters in front of the coasts of Antarctica--could be interpreted as a circle of submarine mountain ranges. In other words, a circle of least resistance of the Earth's crust to pressures acting from all sides upon the South Polar Continent. The shape of this Continent is that of a twisted pear. Palmer Archipelago, the South Shetlands, and the South Orkneys may be considered as parts of the stem of this continental pear, pushed towards the northwest and north of the axis of the Antarctic Andes. And this bending of the Antarctic Andes is symmetrical to the arc of the Andes of southern Terra del Fuego. The rocks of both chains of mountains are similar. But now we have the result of a push from west to east and a discontinuity marked by a loop, a flexure indicating a north-to-south displacement of the South American Continent. The island-arches between North and South America may be the effect of a similar displacement.

An oceanographer may advise us to avoid improbable products of pure imagination. A volcanologist, on the contrary, may perhaps add even more hypothetical considerations and ask other geophysicists for help. Since the intrusive and eruptive rocks, belonging to different geological ages, are not the same, a volcanologist could probably give most valuable interpretations of gravimetric cross-sections across old, geologically middle-aged,and recent mountain ranges made where eruptions took place. A study of structure and porosity of the rocks, as well as specific gravities and contents of water and gases, would have to be supplied by collaborating geochemists.

(3) Meteorology forms one of the Sections of the American Geophysical Union. We may ask what kind of studies of our atmosphere may serve as contributions to the knowledge of continental and oceanic structure. If an astronomer were to ask a meteorologist for information, he would be interested in the hypothetic role of our atmosphere. First, he would want to know from the meteorologist especially interested in the study of the day-to-day changes of distribution of atmospheric pressure, or persistent changes of rainfall, the extent such changes could affect very slight displacements of the center of gravity of the Earth. And then he would ask a climatologist if he could explain the great differences, observed from year to year, in the amplitudes of annual variations of latitude.

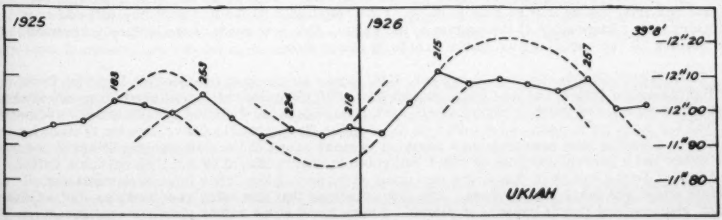

Fig. 1--Latitude-variation, Ukiah, 1925-26

Most meteorologists and climatologists may consider both questions as belonging to the history of opinions. But suppose that the astronomer were more specific in his query of investigators attempting to give a satisfactory answer. Suppose he might have said to me: "Look at this Plate 2 of Kimura's volume on Results of the International Latitude Service from 1922.7 to 1931.0. Do not pay any attention to the curve in red, the result of interpolations. This curve simply shows a more or less regular annual variation, with a superposition of a presupposed period of 433 days." I would have immediately added that the black curve of connected dots of means, 12 in a year, is a misinterpretation and that the plate should be put in the form of Figure 1. In 1925 and 1926, for example, we should have a maximum between the dots 183 and 253 and the same in 1926 between 215 and 257. Neither can we admit that the dots of the minimum (224 and 218) are out of place. Therefore, we have to admit discontinuities--surelevated minima and subsidence of maxima. This is just what we may observe on curves of annual variations of atmospheric pressure. And from then on we might discuss cause and effect for hours.

(4) How about the weather man, does he not have something more to say? Continental topography and ocean-currents complicate to a great extent the simplicity of changes of weather that should occur under a direct influence of a variable solar radiation--variable both in quality and intensity.

You all know something about the results of the persistent work of Dr. ABBOT. This persistency of credo during a life's work may serve as an example. It was mainly because of the constant free exchange of ideas and eventual criticism that Dr. Abbot helped me to accumulate endless proofs, for a thesis, showing that the changes of distribution of pressure from day to day are a direct effect of changing solar impulses. I am convinced that this assertion will have to be accepted.

To recapitulate my argument, let me say that after formulation by many of the problems to be solved, well-prepared specialists should be set at work independently on selected ones, while others should be assigned for attack by the staffs of existing institutions.

R. M. FIELD--Mr. Chairman, may we now call on the representatives of the Navy and of the Coast and Geodetic Survey for any comments?

GEORGE S. BRYAN (Hydrographer, United States Navy)--The part that the Hydrographic Office plays in this connection is one of collecting information. We have been obtaining deep-sea soundings for many years. I do not think many of you realize the enormous number of soundings taken by the Navy in recent years. In addition to that, we have also carried out gravity-expeditions in the Caribbean, taken dynamic soundings in various places in connection with our survey-projects, and collected a vast number of ocean-current and temperature observations which are now being published.

We do not attempt to interpret any of this information because we do not know enough about it. We leave that to the scientists, but are contributing by supplying data when we can. I had a letter from the National Research Council a few years ago in which they asked us to extend the United States Coast and Geodetic Survey's work on the Atlantic Coast canyons farther out to sea. I had to decline at the time because of the emergency of national defense and we were unable to spare a ship, but expressed the hope that some day after peace was declared such an expedition could be made. I can only say that if it lies within my power to make the decision, we will continue to carry on the other work the same as in the past, particularly soundings. On account of the war, our soundings have been curtailed. We have a number of them which we do not want to publish for natural reasons, but we will be able to do so at the conclusion of the war and they will add considerably to our knowledge of the bottom of the ocean. Our new chart of the Antarctic, however, will include all the soundings available to date in this region.

T. H. WHITCROFT--During September, 1939, I was assigned to the Oceanic Sounding Desk in the Hydrographic Office. At that time, we had about 750,000 miles of unpublished deep-sea soundings; all of these, and those received since, have been indexed and plotted. Many areas have been studied and selected soundings published on the regular Hydrographic Office charts. This large amount of sounding data necessitates a revision in many areas of the Bathymetric Chart of the Caribbean and a general revision of other bathymetric charts issued by the Hydrographic Office. As Admiral Bryan has said, due to the war many activities of the Office have been curtailed, oceanic soundings being among these. The few soundings that are being received are studied, indexed, and anything that is unusual is plotted. I have found some rather peculiar configurations that will be of great interest to all of us, especially the Section of Oceanography. But to discuss them, we will have to wait until this struggle is over.

O. H. GISH--I should like to discuss further contributions that might be made from the field of terrestrial magnetism and electricity. Nothing has been said of the bearing which electrical phenomena of some sorts may have on this problem of structure. I have harped on this before but I think it should be mentioned here that measurements and surveys of the electrical currents (or gradients) within the Earth in selected regions would certainly help to reveal hidden structure. Although it would require the work of a mathematical physicist to develop methods for extracting quantitative conclusions, yet even without that one can doubtless use electrical surveys for improving the qualitative picture of hidden structure. I am thinking now of structure that probably lies in the region not so readily explored by other geophysical methods. The magnetic foci of secular change mentioned by Dr. Fleming are believed to indicate changes in structure at depths several hundred kilometers below the surface of the Earth. Certain types of magnetic anomalies reveal more superficial conditions. Electric currents in the Earth have characteristics which definitely indicate that these currents are modified by structure not evident on the surface in many cases, and to me it seems that this would be of interest to geologists because of its possible bearing on the structure at depths not reached by ordinary geophysical exploration and yet probably not so deep as structural features more readily revealed by seismic observations and by magnetic phenomena such as were referred to by Dr. Fleming.

W. T. THOM, JR.--Those of us who heard Dr. JOLLIFFE'S paper, given at the annual meeting of 1942, will recall that his maps and aerial photographs of northwestern Canada showed visible traces of a great pre-Cambrian fault-system, much like the present San Andreas fracture-system of California. Differential horizontal movements on several of the faults shown us by Dr. Jolliffe had amounted to from two to ten miles and, if I remember correctly, a horizontal movement of 30 miles or more was indicated along one fracture. Similar differential horizontal movements of crustal segments have taken place in connection with mountain-building at many times in the geologic past, and seismic, geodetic, and geologic evidences assure us that this kind of differential movement is still in progress in island-arc regions and in seismic areas such as that of southern California, where careful studies by Buwalda, Byerly, Gutenberg, Richter, Wood, and others have revealed a continuing tendency toward relative shift southeastward of the blocks lying northeast of the San Andreas Fault and related fractures--including one (the Buena Vista Fault) on which progressive movement has been made manifest by the continued shearing of well-casings and by the buckling of oil pipe-lines.

Speaking on behalf of the Special Committee on Geophysical and Geological Study of Continents of the American Geophysical Union, I am certain that the International Commission on Continental and Oceanic Structure has a wonderful opportunity to get to the roots of some of its largest problems by stimulating international cooperation on the collection of quantitative data (1) on the nature and amount of past crustal shifting--as revealed by geologic evidence--and (2) on the rates and directions of present crustal shiftings as revealed by geodetic, seismic, and topographic evidence.

L. B. TUCKERMAN--What has become of the international stations for checking variations of latitude and longitude?

C. L. GARNER--The Coast and Geodetic Survey maintains two variation-of-latitude observatories, one at Ukiah, California, and the other at Gaithersburg, Maryland. Observations at these two stations were begun in 1899 under the auspices of the pre-World-War-I International Geodetic Association (Internationale Erdmessung). The observations at Ukiah have been continuous since 1899. The Gaithersburg Observatory also has obtained data from about 1900, except during the years 1915 to 1932.

These are two of the five stations operated in accordance with an international program. The other stations are at Kitab (U.S.S.R.), Mizusawa (Japan), and Carloforte (Italy). They are known to have been in operation up to the outbreak of war in 1939.

Many of the leading astronomers of the country have strongly recommended the continuation of the latitude-observatories in the United States without interruption during the war. Some have recommended the addition of a third station in order to compensate somewhat for the very probable loss of work at stations in other parts of the world, since it is doubtful whether all of the stations continue in operation.

Before the war the original records were sent to the Central Office of the International Service at Naples. Since December 1941 both original and duplicate records have been held in this country

A program of observations to determine the differences in longitude between stations in various parts of the world was last carried on in 1933. The purpose of this campaign, which was

to be repeated at intervals, was to see whether there were changes in longitudes that might be interpreted as indicating a continental drift of the Wegener type. This time the United States observed a station at Honolulu, Territory of Hawaii. Copies of the records of all this work were sent to the Central Office in Paris.

Mr. LAMBERT or Dr. STETSON, who is present, is well qualified to discuss the various problems involved in both the variation-of-latitude observatories and the determination of differences of longitude.

H. T. STETSON--Captain Garner's remarks in regard to the stations for observation of variation of latitude raises a few problems that should be of concern in this discussion. It may be remembered that these international stations were established along the thirty-ninth parallel at Gaithersburg (Maryland), Cincinnati (Ohio), Mizusawa (Japan), Charjui (Turkestan), and Carloforte (Sardinia).

Students of the Earth will immediately recognize that all but Gaithersburg and Cincinnati are in seismically unstable territories. The station at Cincinnati was the first one abandoned, chiefly, as I recall, because the variations in latitude there were found to be not so well in accord with those of the other stations. The station at Gaithersburg was abandoned for a time but fortunately later reestablished; even this station is near the continental shelf and may entail some unanticipated variations on account of its location near the coast.

It will be recalled that the stations were originally set up from the point of view of determining the motion of the instantaneous pole of rotation of the Earth and that in the reduction of the observations under the Latitude Commission of the International Astronomical Union declinations of the stars have been corrected when necessary to bring about the best conformity for the various latitude-stations reporting without raising the possibility of geographical shifts of coordinates at the observatories involved.

The discussion here this afternoon, notably the remarks of Professor Thom relative to marked lateral shifts in the Earth's crust currently taking place, suggests that it may have been unfortunate that discrepancies among the latitude-stations should have been brought into agreement by arbitrarily correcting the declinations of the stars from which the latitudes were determined. This is an outstanding example of the necessity of understanding a fundamental problem in the basic Earth-sciences that crosses several departments of scientific knowledge. The time seems not far distant when these observations may need to be reexamined from the point of view of the consideration of the possible shift of the geographical coordinates of the observing stations as well as of determining the motion of the pole. It would also seem highly desirable that a latitude-station be established in the mid-continental territory as far distant from orogenic and seismically active zones as was the original station at Cincinnati.

As for the consideration of small variations in longitude to which Captain Garner has referred, the problem in some respects is simpler and in other respects more complicated. It is simpler in that the absolute positions of the stars are not involved since longitude is but the difference in time of transit of the same stars at the Greenwich meridian and the meridian of any other station.

Unfortunately, however, determinations of longitude are complicated by the necessity of the exchange of time-signals which involves radio communication. There already seems to be sufficient evidence that the apparent time of propagation of radio waves over large distances is somewhat variable--the apparent velocity quite likely being dependent upon conditions of the ionosphere as well as upon the geomagnetic coordinates of the path of transmission.

The whole problem of the evaluations of real changes in geographic coordinates is an excellent illustration of one of those instances where the solution depends upon transgressing the boundaries of any single science. This has again and again been emphasized in the discussion this afternoon. Astronomy, geodesy, and radio engineering are certainly as much concerned as structural geology in the absolute evaluation of crustal movements. All triangulation can at best be but differential. There appears to be no way of determining absolute shifts except in determining positions from the stars as a navigator does in determining the position of his ship from celestial observations. Utilizing our present knowledge of radio-wave propagation, frequencies and transmission-paths for time-signals could be selected so as to minimize these variations. In this way a higher degree of accuracy with the elimination of certain systematic errors could undoubtedly be attained in determinations of longitude.

J. A. FLEMING--I would like to thank you all, on behalf of the Union, for making the twenty-fourth annual meeting so successful. The meeting now stands adjourned.

AMERICAN GEOPHYSICAL UNION

TWENTY-FOURTH ANNUAL MEETING

SECTION OF GEODESY

REPORTS AND PAPERS

Washington, D. C.
April 24, 1943

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TRIANGULATION-ADJUSTMENT BY INTERNATIONAL BUSINESS MACHINES

C. A. Whitten

At the last meeting of this Section, Major Frank L. Culley of the United States Corps of Engineers presented a paper describing the application of punched-card methods of computing to the computation of military-grid coordinates. Although the members of the Division of Geodesy of the United States Coast and Geodetic Survey have been interested in the development of scientific computations by the punched-card method, it was only about a year ago that the opportunity to investigate the application of such methods to the adjustment of triangulation first presented itself. In view of the success of the former project, it was felt that the time and expense involved in an investigation of the application of these methods to triangulation-adjustments would be well justified.

Dr. W. J. Eckert [see W. J. ECKERT, Punched-card methods in scientific computation] of the United States Naval Observatory assisted in the preliminary study of the problem. His suggestions and criticisms were very helpful in the general development of the procedure. He arranged for a test of the procedure on the machines in the Watson Astronomical Computing Bureau of Columbia University, New York City. Miss Lillian Feinstein of that Bureau also assisted in these preliminary tests.

After the completion of these preliminary machine-tests, further tests were made on the machines of the United States Bureau of the Census, where Don Heiser and Ernest Kimball gave many valuable suggestions. Due to the fact that the machines at Columbia have special features attached and the machines at the Bureau of the Census are standard, a few changes in procedure had to be made.

All of the tests indicated that the formation of normal equations from correlate equations was not efficient. This would not be true for the formation of normal equations from statistical data where thousands of observations with a few unknowns are involved.

The forward solution of the normal equations can be solved by an application of Gauss' method and a machine-principle of "crossfooting" [A + ($\pm$B)x($\pm$C) = D]. A given set of n equations is reduced one in number by eliminating the first unknown from all of the equations. This procedure is repeated until only one equation with one unknown remains. The back solution involves the substitution of unknowns in consecutive equations, determining the value of an additional unknown after each substitution. Again the "crossfoot" principle is involved. The computation of the corrections to the observations, or "v's", and the substitution of these corrections in the original condition-equations involve unit-multiplication and addition. The computed results are readily tabulated.

After tests were made on a sample-adjustment, a complete set of 96 normal equations was solved. The adjustment selected was for area-triangulation of a scheme involving 23 new stations, eight previously adjusted stations, 84 newly observed lines, 11 "fixed" lengths, and a first-order base. The 96 condition-equations needed in this adjustment were so interlocking that approximately 25,000 multiplications were needed to complete the solution and compute the corrections.

Because of the fact that the solution of equations is a progressive computation, the maximum efficiency of the machines could never be attained. Any error would delay the operation until all corrections had been made. The machines and operators would occasionally make mistakes which were difficult to locate for the check-system merely indicated that an error had been made. In the elimination of a single equation in the forward solution, a sorter, reproducer, multiplier, and tabulator had to be used in sequence with the final check obtained after the tabulation had been made. Since only a few cards, two to six hundred, are involved in any one operation, it is not practical to devote too much time to checking machine-operations. However, an error in any part of any of the various steps involved would be very troublesome.

These tests and results of an actual solution lead to the following conclusions:

(1) Normal equations for triangulation-adjustments can be solved efficiently by punched-card methods, provided the machines are in excellent adjustment, the operators are well trained, and a mathematician who is familiar with all phases of the problem is available to help locate errors.

(2) There is no indication of any saving in cost unless the machines were needed for many other types of work so that problems of this nature could be solved on the "idle time" of the machines.

(3) Geodetic computations of a progressive nature in general are not the best type of problem to solve on the punched-card machines. A computation of a table where checks are obtained by differencing, or the conversion of data from one form to another where each unit is independent, are better types of scientific computing to be applied to the punched-card methods.

(4) The possibilities of the machines are unlimited and only through a complete understanding of the machines as well as the problem can the maximum efficiency be obtained.

U. S. Coast and Geodetic Survey,
Washington, D. C.

AZIMUTH-DETERMINATIONS IN HIGH LATITUDES

H. J. Seaborg and C. H. Swick

In connection with recent triangulation in Alaska it was necessary to observe a number of Laplace azimuth-stations between the south coast and Fairbanks and down the Yukon from Fairbanks to Norton Sound. Lieutenant Seaborg was detailed to make the necessary astronomical azimuth- and longitude-determinations on this project. He was also instructed to make latitude-observations at each station if this could be done without serious delay to the progress of the work, although latitudes are not necessary for Laplace control. In order to facilitate the azimuth-determinations, a special method was devised by Mr. Swick for use in high latitudes which seemed to work out quite satisfactorily in this region.

Precise azimuth-determinations are difficult to make in high latitudes. The standard method of Polaris observations with a theodolite is unsatisfactory in latitudes much above 50°. All of Lieutenant Seaborg's stations, eight in number, were between latitudes 61° and 65°. A small error in the leveling of the horizontal axis of the instrument will cause serious uncertainty in the azimuth when the pointing on the star must be made at such a high angle of elevation. If the horizontal axis of the instrument is at right-angles to the vertical axis, as it should be, the error will not be reversed by reversal of the instrument, and therefore cannot be eliminated in this manner.

The method which had been used in the past for azimuth-determinations in Alaska was preferable to the standard theodolite-method but was not entirely satisfactory. It involved the use of an astronomical transit, as does the method about to be described, but did not lend itself to convenient repetition of observations or to high accuracy. In this older method a pointing was made on a mark set north or south of the station, in the collimation-axis of the instrument, after each longitude-determination at a station. The azimuth of this pointing was then derived by taking into account the azimuth- and collimation-errors of the instrument as obtained from the longitude-computations. One azimuth-observation was thus obtained for each longitude-determination or, under normal conditions, from three to five observations at each station.

In the method here described, the azimuth-observations are made entirely independently of the longitude-observations. They can be made quite rapidly and with any desired number of repetitions. About 40 repetitions were made at each station in about three hours by Lieutenant Seaborg. The method consists essentially of measuring with the eyepiece-micrometer the small angle, never greater than about 25′, between the horizontal direction of Polaris and that of a mark set nearly in the same azimuth (or 180° different). It is desirable to make the observations when Polaris is near elongation in order that its movement in a horizontal direction will be slow and that several observations may be made before the star moves beyond the safe range of the instrument, that is, moves too close to the edge of the field of view.

With the exception that the angle measured is necessarily small, the method is almost the same as the standard method using a theodolite. For high latitudes, however, the astronomical transit, particularly the "broken-telescope" type, has several advantages over the theodolite. It has greater stability due to its size and weight. It has a longer horizontal axis and a longer and more accurate stride-level, a very important consideration in bringing the direction of Polaris down to the horizon from an altitude of 60° or more. The eyepiece is conveniently located for the observer and is always in the same location whether the instrument is pointed on Polaris or on the mark.

One technical detail should be mentioned as a caution to anyone wishing to use the method. The micrometer-reading on Polaris must be multiplied by the secant of the altitude to reduce it to the corresponding angle at the horizon. Only the collimation-axis projected moves along a great circle of the celestial sphere when the telescope is turned on its horizontal axis. The pointing wire, if away from the collimation-axis, will move on a small circle parallel to the great circle described by the collimation-axis and a correction must therefore be applied. Also, if the mark is at an elevation considerably different from that of the instrument (elevation-angle greater than 1°, plus or minus) a similar correction must be applied to its micrometer-reading.

The method has one requirement which is sometimes difficult to meet. A mark must be set about 2° away from the meridian and at a distance of two to five miles from the station, if possible. This mark may be either north or south of the station occupied but must be closely at the same azimuth as Polaris at elongation (or 180° different). It should be placed, if possible, where it can be made a station of the triangulation-net, or at least where it can be accurately connected to the net, by a closed triangle, if possible. Except in flat, wooded terrain, this requirement can be met without too much difficulty by a little care in the selection of the Laplace station.

Two different orientations of the instrument are required at each station, one in the meridian for the longitude- and latitude-observations and the other about 2° out of the meridian for the azimuth-observations. Polaris was conveniently at eastern elongation at the time of night best suited for the azimuth-work in Alaska. In orienting the transit for the azimuth-observations it was desirable to have it point from 5′ to 10′ to the westward of Polaris at elongation in order that the observations might extend over a fairly long period and have the mean position of Polaris near the collimation-axis. The mark was placed near this desirable azimuth of the collimation-axis.

For part of the work in Alaska, the astronomical party was behind the triangulation-party. At these stations the desired orientation of the instrument was computed by use of Table V in the American Ephemeris and an angle was turned from some line of the triangulation with a small engineer's transit to give the line to the desired position of the mark. If it became necessary to place the mark a little to one side of this line because of terrain-conditions, allowance was made for this in the later orientation of the instrument. During the latter part of the season, the astronomical party was ahead of the triangulation-party and the orientation was done by means of star-sights or in other ways.

The instrument was supported on an aluminum tripod. This tripod was oriented for a direction about half-way between the meridian and the mark. In this position it could be used both for the azimuth-observations and for the latitude- and longitude-observations as the instrument could be shifted sufficiently on the tripod-head to change from one orientation to the other. In either position it was fastened to the tripod-head with plaster of Paris for stability.

The setting of the mark at each station was done in the daytime. The necessary signalling between the observer at the station and the men setting the mark, in order to get the desired alignment, was done with flags. After the mark had been set and a signal lamp placed over it, the final adjustment was made of the instrument-pointing. Each time the instrument was shifted in position it had to be releveled and its plumbing over the mark had to be checked. It usually took about an hour to perfect the pointing of the instrument after the mark had been set. In order to avoid bias in the micrometer-pointings on the mark, in the observations to be made later, the collimation-axis of the instrument was oriented two or three minutes to one side of the mark instead of on it.

Since the Bamberg transit was not designed as an azimuth-instrument, it has no special means for plumbing it over the mark. The plumbing was done with a small engineer's transit from two points about 100 feet away from the instrument, the lines from which made an approximate right-angle at the station. The telescope of the Bamberg was pointed to the zenith during this operation and a small rod at the base of the vertical part of the telescope-tube was taken to be identical with the collimation-axis. The error in this assumption was undoubtedly very small, a few millimeters at most.

As may well be surmised, astronomical work in Alaska is difficult. There is a great deal of rainy and cloudy weather, especially along the coast and in the mountains. Transportation is slow and uncertain. Trucks were used along the Alaska Highway, but the road was in very poor condition when the season's work was started early in May and the trucks were frequently bogged down. Commercial planes were used for transportation down the Yukon, but because of unusual activity in that area many long waits were necessary. Two of the men got caught by snow at Norton Bay and had to wait a month until a ski-plane could pick them up. Radio reception was extremely poor

at times and the severe curtailment of the number of time-signals per day which was made about a year ago was a great handicap to the party although it was partly relieved by special signals which the Naval Communications Service and the Naval Observatory very kindly furnished for this project. Eight stations were determined during the season with latitude, longitude, and azimuth observed at each, except for one missing latitude. The probable errors of the azimuths averaged about two-tenths of a second and the latitudes and longitudes were also of high accuracy.

U. S. Coast and Geodetic Survey,
Washington, D. C.

GRAVITY-ANOMALIES AND MERIDIAN DEFLECTIONS IN HAWAII

J. A. Duerksen

The Hawaiian Islands form a chain of volcanic mounds on a fairly level ocean-floor. The largest and most recent are at the southeast end of the chain. There are still several active volcanoes on Hawaii, the largest island of the group. The Coast and Geodetic Survey has 19 astronomical latitude-observations and 15 gravity-determinations on the larger islands of the Hawaiian group. The large positive isostatic gravity-anomalies and the isostatic deflections in the meridian indicate very definitely that the Hawaiian Islands are by no means isostatically compensated. Major William Bowie and C. H. Swick have frequently called attention to the large positive gravity-anomalies indicating the uncompensated island-masses. In 1924, Mr. Swick computed the density of the island-blocks of Hawaii and Oahu from the gravity-anomalies at Mauna Kea and Honolulu, respectively, assuming the extra mass to be in the island-blocks. The islands were assumed to be compensated. He arrived at a density of 3.62 for Hawaii and 3.34 for Oahu. In his studies of the gravity-anomalies in the Hawaiian Islands, Roy W. Goranson [The density of the Island of Hawaii and density distribution in the Earth's crust, Amer. J. Sci., v. 16, pp. 90-120, August 1928] comes to this conclusion: "The inference is, too, that the volcanic islands of the Pacific are essentially uncompensated (sinking) loads on the sub-Pacific crust."

In an unpublished manuscript of a study of the deflections in the meridian, written about 1930, Hugh C. Mitchell concludes: "Complete isostatic compensation does not exist in the Hawaiian Islands, but rather, because of isostatic lag, only outer areas reaching to within some 200 kilometers of the islands are compensated, ... surface-density of the islands is greater than that accepted for the general surface of the Earth (2.67) and may be somewhat greater than that obtained from a consideration of analyses of surface-specimens (2.88)."

The purpose of this paper is to use the geologists' best estimates of the density of the islands and then determine from the gravity-data the necessary increase in density of the sub-island part of each compensation-block of the crust for making the average gravity-anomaly equal to zero. This increase in density is then used to determine the new deflections of the vertical in the meridian.

The islands of Oahu and Hawaii are used in this investigation because the largest number of determinations are on these islands. There are six gravity-stations on each island, fairly well spaced, and there are four latitude-stations on Oahu and seven on Hawaii. For Oahu, only the three latitude-stations published in Special Publication No. 156 have been used in this investigation.

In reply to an inquiry relative to the average density of the islands of Oahu and Hawaii (surface to average ocean-floor), Dr. K. T. Stearns, Hawaiian geologist of the United States Geological Survey, writes that his estimate of the average gross density of the island-blocks is between 2.75 and 2.80. He states further that none of the Hawaiian geologists believe the density to be more than 2.8. Dr. C. K. Wentworth believes the gross density is of the order of 2.6. In accordance with these estimates, and for convenient use of our tables which are based on a 2.67 density, the density of 2.67 has been used for computing the effect of the islands from the surface to the ocean-floor.

Each island, Hawaii and Oahu, has been treated separately. For the sake of limiting the island-mass and using the same assumption for each station on an island, the 500-fathom curve has been taken as the boundary of each island, except that between Oahu and Molokai the depth of the ocean does not reach 500 fathoms and so the line midway between those islands has been taken as the southeastern boundary of Oahu. The island-block of 2.67 density is thus assumed to extend from the general ocean-floor (2500 fathoms below sea-level) to the surface, bounded by the 500-

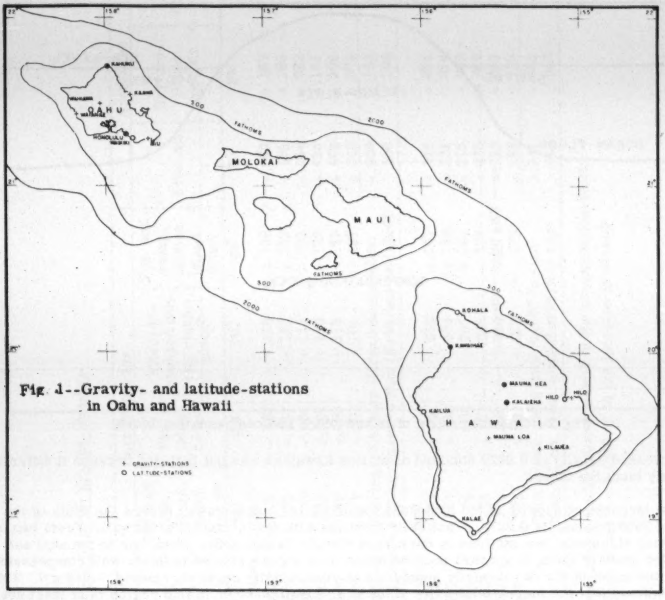

Fig. 1--Gravity- and latitude-stations in Oahu and Hawaii

fathom depth-curve. That part of the crust directly beneath the island-block extending to a depth of 113.7 kilometers below sea-level is labelled compensation-block, although in this case it will not turn out to be a compensation. Figure 1 shows the principal islands, gravity-stations, latitude-stations, and the 500- and 2000-fathom curves. Figure 2 illustrates the assumptions outlined above.

For each gravity-observation, three anomalies were computed--the free-air, Hayford-Bowie isostatic, and a so-called special anomaly.

The free-air and the Hayford-Bowie isostatic anomalies were computed according to standard procedure. The depth of compensation for the Hayford-Bowie isostatic anomalies is 113.7 kilometers.

For the special anomalies, the corrections for topography and compensation for the entire world beyond the island-block boundary were taken identical with the Hayford-Bowie corrections. The topography-correction for the island-block itself was also obtained by using the Hayford-Bowie tables. The increased density of the compensation-block above normal was then computed from the remaining positive anomalies. By normal density is meant the density of this corresponding layer for a sea-level station, that is, for a station on land at sea-level elevation.

Thus, the increase of density of the Hawaiian compensation-block, above normal, was computed separately for each station on Hawaii, and similarly for Oahu.

The average increase of density as obtained from the gravity-stations for the Oahu compensation-block was found to be 0.0505, the individual values varying between 0.0275 at Kahuku on the northern tip and 0.1028 at Waianae on the west coast. The average increase of density for the Hawaii compensation-block was found to be 0.0676, the individual values used varying between 0.0419 at Hilo on the east coast and 0.0840 at the top of Mauna Loa, near the center of the island.

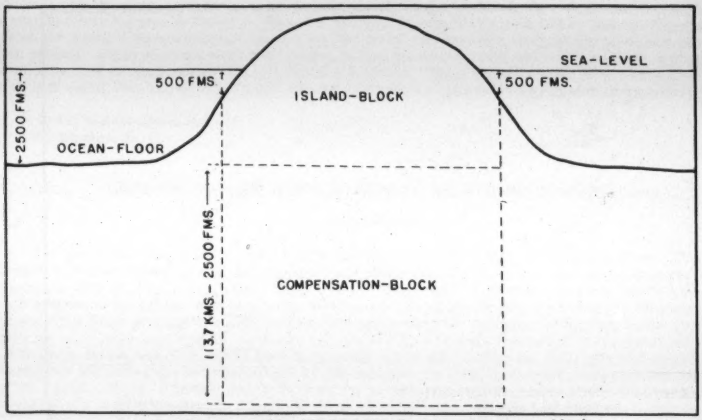

Fig. 2--General profile of island-block and compensation-block

The increased density of 0.0029 obtained at station Kawaihae was not included because it differed so widely from the others.

The increase of density of the compensation-block for a sea-station (where the depth of the ocean is 2500 fathoms)is 0.0673, practically identical with that obtained for Hawaii. From two of Dr. Vening Meinesz's sea-stations in the deeper Pacific Ocean in this area, one to the east and one to the south of Oahu, it appears that the ocean in this general area is fairly well compensated; in fact, the mean of the two isostatic anomalies is even slightly negative, namely, -.018 gal. This would indicate that the increased density of the compensation-layer in this region is at least not greater than 0.0673. The computed increase of density of the Hawaii compensation-block is thus about the same as the compensation-block under the ocean in this area. It appears, therefore, that the island of Hawaii is entirely uncompensated. For Oahu, the increase in density is about 25 per cent less. Hence, there seems to be an indication that Oahu is partly compensated, which is in agreement with geological evidence. Geologically speaking, Oahu is the older of the two and thus should have had more time than Hawaii to become compensated by sinking and erosion.

The special gravity-anomalies were then computed for each island, using the average increase of density of 0.0505 for the Oahu compensation-block and 0.0676 for the Hawaii compensation-block.

On the island of Oahu, the special anomalies thus computed range from -0.026 to +0.059 gal, where the Hayford-Bowie anomalies range from +0.029 to +0.120. The average anomaly, of course, has decreased very nearly to zero as it should, but the total range between stations has decreased only very slightly from 0.091 for the Hayford-Bowie to 0.085 gal for the special anomalies.

On the island of Hawaii, the special anomalies vary between -0.038 and +0.028 gal as against +0.022 to +0.209 gal for the Hayford-Bowie anomalies. Here the total range has decreased greatly, namely, from 0.187 gal for the Hayford-Bowie to only 0.066 gal for the special anomalies.

Table 1 shows a comparison between the free-air, Hayford-Bowie isostatic, and the special anomalies.

The Hayford isostatic deflections of the vertical in the meridian were computed for each one of the latitude-stations on these islands. The special deflections were then computed on the basis of the same assumptions as for the gravity-stations, using the increase of density of the compensation-block for each island separately.

Table 1--Principal facts for gravity-stations

Station No.	Station Name	Latitude	Longitude	Elevation	Observed gravity	Theoretical gravity	Corrections for: Elevation	Corrections for: Top. and comp. Hayford-Bowie 113.7 km	Corrections for: Top. of Island d=2.67	Corrections for: Effect increased density comp.-block[b]	Corrections for: Top. and comp. outside island-block	Anomalies: Free-air	Anomalies: Hayford-Bowie isostatic	Anomalies: Special
		° ′	° ′	meters	gals	gals	gals	gal	gal	gal	gal	gal	gal	gal
							Hawaii Island							
2	Mauna Kea	19 48.9	155 28.8	3981	978.074	978.641	-1.229	+.475	+.388	+.116	+.158	+.662	+.187	.000
3	Kalaieha	19 42.2	155 27.9	2030	978.504	978.635	-0.626	+.305	+.217	+.123	+.153	+.495	+.190	+.002
4	Kawaihae[a]	20 02.1	155 49.4	2	978.817	978.654	-0.001	+.142	-.004	+.113	+.163	+.164	+.022	-.108[c]
5	Kilauea	19 25.9	155 15.7	1211	978.673	978.619	-0.374	+.262	+.132	+.110	+.172	+.428	+.166	+.014
6	Mauna Loa	19 29.8	155 34.8	3970	978.096	978.623	-1.225	+.489	+.403	+.115	+.152	+.698	+.209	+.028
7	Hilo	19 44.0	155 03.1	5	978.883	978.636	-0.002	+.173	-.001	+.101	+.187	+.249	+.076	-.038
							Hawaii Island, mean with regard to sign (Kawaihae excluded)					+.506	+.166	+.001
							Hawaii Island, mean without regard to sign (Kawaihae excluded)					.506	.166	.016
							Oahu Island							
1	Honolulu	21 18.1	157 51.8	6	978.951	978.729	-.002	+.173	+.001	+.070	+.167	+.224	+.051	-.014
8	Niu	21 17.1	157 44.1	2	978.948	978.728	-.001	+.167	+.002	+.070	+.158	+.221	+.054	-.009
12	Kahuku	21 42.4	157 58.5	2	978.968	978.754	-.001	+.186	.000	+.057	+.184	+.215	+.029	-.026
13	Kaawa	21 32.4	157 50.6	1	978.980	978.744	-.000	+.174	+.002	+.065	+.173	+.236	+.062	-.004
14	Wahiawa	21 29.6	158 02.0	264	978.912	978.741	-.081	+.199	+.029	+.066	+.171	+.252	+.053	-.014
15	Waianae	21 26.0	158 10.9	3	979.034	978.737	-.001	+.178	+.002	+.058	+.179	+.298	+.120	+.059
							Oahu Island, mean with regard to sign					+.241	+.062	-.001
							Oahu Island, mean without regard to sign					.241	.062	.021

[a]Station Kawaihae was not used in determining the increased density of the compensation-block.

[b]For Hawaii Island $\delta = 0.0676$; for Oahu Island $\delta = 0.0505$; δ is the increase in density.

[c]Not used.

Table 2--Deflections in the meridian

Station	Approx. elev.	Geodetic longitude	Geodetic latitude as published in Sp. Pub. No. 156	Geodetic latitude assumed datum	Astronomical latitude	Corrections			Deflections in meridian		
						Top. and comp. Hayford, depth of comp. = 113.7km	Topography	Comp. for outside of block + effect of increased density of comp.-block[a]	Observed	Isostatic Hayford	Special
	meters	° ′ ″	° ′ ″	° ′ ″	° ′ ″	″	″	″	″	″	″
Hawaii Island											
Kohala	0	155 46 27.15	20 14 58.21	20 14 48.21	20 15 29.33	+20.32	+27.36	+8.17	+41.12	+20.80	+5.59
Kawaihae	0	155 49 26.04	20 02 05.67	20 01 55.67	20 02 05.87	+ 4.12	+ 5.37	+9.01	+10.20	+ 6.08	-4.18
Mauna Kea	3980	155 28 47.08	19 48 51.67	19 48 41.67	19 48 51.54	+ 3.66	+ 4.33	+6.03	+ 9.87	+ 6.21	-0.49
Kalaieha	2030	155 27 51.68	19 42 14.62	19 42 04.62	19 42 02.45	- 3.21	- 9.44	+8.15	- 2.17	+ 1.04	-0.88
Hilo	0	155 05 57.66	19 43 11.59	19 43 01.59	19 43 11.24	+ 7.09	+ 5.23	+5.60	+ 9.65	+ 2.56	-1.18
Kailua	0	155 59 48.45	19 38 44.41	19 38 34.41	19 38 20.86	-11.44	-23.61	+9.80	-13.55	- 2.11	+0.26
Kalae	0	155 41 03.86	18 54 59.36	18 54 49.36	18 53 51.72	-39.95	-67.69	+9.74	-57.64	-17.69	+0.31
				Hawaiian Island, average deflection with regard to sign					- 0.36	+ 2.41	-0.08
				Hawaiian Island, average deflection without regard to sign					20.60	8.06	1.84
Oahu Island											
Kahuku	0	157 58 59.79	21 42 41.55	21 42 31.55	21 43 06.07	+20.36	+33.39	-6.92	+34.52	+14.16	+8.05
Honolulu	0	157 51 44.71	21 18 28.06	21 18 18.06	21 18 02.51	- 6.23	- 4.66	-2.82	-15.55	- 9.32	-8.07
Waikiki	0	157 50 01.18	21 16 52.23	21 16 42.23	21 16 24.39	- 6.86	- 5.99	-2.11	-17.84	-10.98	-9.74
				Oahu Island, average deflection with regard to sign					+ 0.38	- 2.05	-3.25
				Oahu Island, average deflection without regard to sign					22.64	11.49	8.62

[a]For Hawaii Island $\delta = 0.0676$; for Oahu Island $\delta = 0.0505$; δ is the increase in density.

It should be remarked here that the islands of Oahu and Hawaii are connected by triangulation. Hence, all stations are on the same geodetic datum. The latitude-datum used in Special Publication No. 156 was decreased by 10" in order to bring the average of all deflections more nearly equal to zero.

On the island of Oahu, the Hayford deflections vary between -10".98 and +14".16 while the special deflections vary between -9".74 and +8".05. The total range has decreased from 25".14 to 17".79.

On the island of Hawaii, the Hayford deflections vary between -17".69 and +20".80 while the special deflections vary between -4".18 and +5".59. The total range has been reduced here from 38".49 to 9".77.

Table 2 gives a comparison between the observed, Hayford isostatic, and special deflections.

Conclusion: If the density of the Hawaiian Island blocks of Oahu and Hawaii is equal to about the average density (2.67) of the Earth's surface crust, in accordance with the estimates of the leading geologists of Hawaii, then it appears from the limited number of gravity-observations that the Island of Hawaii is an extra load on the Earth's crust and the Island of Oahu is partly compensated.

By using the data obtained from the gravity-stations, the deflections of the vertical are decreased very considerably, particularly for Hawaii. Hence, it may be said, the deflections of the meridian corroborate the gravity-results at least in a general way.

U. S. Coast and Geodetic Survey,
Washington, D. C.

BEHAVIOR OF THE EQUI-ANGULATOR

Weld Arnold
(Presented by Thomas M. Griffiths)

In view of the paper which was given at this meeting last year by Mr. Samuels of the Hydrographic Office, I do not propose to go into a minute discussion of the prismatic astrolabe or the theory of its operation. However, to recapitulate briefly, the prismatic astrolabe was invented by Monsieur A. Claude, of the French Bureau of Longitudes, and Monsieur L. Driencourt, the Chief Engineer of the Hydrographic Office of the French Admiralty.

Essentially, the instrument consists of a horizontal telescope which can be moved in azimuth only and a 60° prism placed in front of the objective with one face normal to the optical axis of the telescope. Below the lower-front face of the prism is placed an artificial mercury-horizon. In operation, the observer sees two images of any star approaching a 60° altitude. Since one image comes directly to the upper face of the prism and one image is reflected upward from the artificial horizon to the lower face of the prism, the two images appear to travel in opposite directions vertically across the field, thus making it possible, by noting when the two images pass each other, accurately to determine the time at which the star reaches a 60° altitude. This altitude may be a few seconds of arc greater or less than 60°, but is constant and dependent upon the internal angle of the prism.

Early models of this French instrument found considerable favor with small scientific expeditions and explorers in back areas, because, for its size and weight, it gave a high order of precision. In 1921, E. A. Reeves, Map Curator and Instructor in Surveying and Practical Astronomy at the Royal Geographical Society, London, devised a means whereby the ordinary theodolite could be converted into a prismatic astrolabe. This Reeves attachment consisted of a 60° prism in a suitable mount which could be placed in front of the objective of the theodolite. A bracket supporting an artificial mercury-horizon was a part of the attachment. By placing the theodolite-telescope in a horizontal position, it became, to all intents and purposes, a prismatic astrolabe. The advent of radio transmission of time-signals about this time added considerable impetus to the use of this instrument for precision-work.

At the outbreak of the present war, the Army Air Forces found itself in great need of a rugged, light-weight precision-instrument which could be used for the determination of latitudes and longitudes for the control of Tri-Metrogon charting projects. After exploring a great many possibilities,

an adaptation of the prismatic astrolabe was decided upon as the best solution of the problem, particularly where weight and bulk with air-borne parties was a prime consideration. This adaptation of the prismatic astrolabe is known as the Equi-Angulator. Its basic design follows in principle the design of the older French model. Speed of operation and a low initial weight per field-party were prime considerations in selecting and designing the instrument which is now in use.

However, another consideration was necessary. This was in the matter of trained personnel. In its simplicity of operation, the equal-altitude method of latitude- and longitude-determinations is hardly to be equalled. This has been particularly true since 1930, when Major Weld Arnold, under the auspices of the American Geographical Society School of Surveying, compiled the first extensive star-lists for the 60° method. These tables have since proved invaluable for parties making use of either the available French instruments, the Reeves attachment, or the newer Equi-Angulator. Prior to that time it was necessary to spend a great deal of time computing star-lists before making an observation.

The probable accuracy of observations made by experienced personnel by this method lies within about 100 feet on the ground. Such accuracy is dependent upon two factors, one of which is controllable and the other not. Any errors in the timing of star-passages will upset this accuracy. Deflection from the vertical will affect the horizontality of the artificial horizon and introduce an error dependent upon the degree of deflection.

In actual practice, the determination of precise time is dependent upon the reception of frequent radio time-signals, thus closely controlling the timepieces which are used for the observation. Deflection from the vertical cannot be dealt with so easily since adequate instruments for the determination of this factor are not available to the Air Forces at this time. Consequently, an effort is made to determine the general character of the country in which the observation is made so that, if necessary, an estimate can be made of the amount of this effect. In any but rugged mountain areas, this is usually not serious. In numerous cases, positions obtained with this instrument by experienced personnel have checked out closely against positions determined by other methods which have taken the geodetic effect into consideration.

In field-operations, the normal procedure is to compute at least four stars from a night's observation as a preliminary check. The reduction is made by the basic formula for the pole-zenith-star spherical triangle and a value for a zenith-distance error between the true and assumed positions determined for each star. The errors are plotted graphically for each star, much as a navigator plots his Sumner line of position and the true position determined from the polygon of position-lines formed. When these stars have been computed, an estimate of the probable cleanness of the observation can be made at once and the party chief can determine whether to move on to the next station or reobserve. No more than these few stars for a preliminary check are computed in the field. The remainder of the field-data is transmitted at once to headquarters, where a final computation can be made under advantageous conditions.

The usual field-party consists of one officer and either one or two enlisted men. It has been found from bitter experience that too many men in a party considerably hamper the speed at which the party can operate. It is particularly necessary that personnel be cut to a minimum where parties are using small aircraft for transportation. Where the party is so large as to require more than one trip by the ferrying aircraft, considerable time is wasted. Under even difficult conditions, three men are usually enough to handle all of the work--movement, sustenance, observations, identification, and field-computation. In a few special cases, where it was deemed advisable to protect the party against hostile natives in back country, the party personnel has been increased.

By the same token, the amount and weight of equipment has been cut to a minimum consistent with accurate results. The basic equipment consists of the instrument, a short-wave radio receiving set, and watches or chronometer, as the case may be. The weight of this basic equipment can be usually held to a maximum of about 100 pounds. To this must be added the personal and camp equipment of the men, necessary forms, tables, and miscellaneous gear. En toto, the weight of party equipment has been pared down as operating units gained more experience in the field until the normal two-man party carries considerably less than the combined weight of the men themselves.

Field-conditions have varied from arctic to tropical ones. Observations have been made at temperatures almost as low as the freezing point of mercury. For some time, a search was made for a suitable horizon-liquid which would not freeze at temperatures below 40°F. However, it was found that the observer and recorder were not capable of really good work at temperatures that

low and the search was abandoned. Ostensibly, the personnel give way before the instrument does.

One of the chief difficulties of operating in arctic temperatures is the collection of frost-particles on the optical parts of the instrument. Whenever any portion of the warm body is brought near the prism, objective, cover glass, or eyepiece in low temperatures, a film of frost will collect on the part. To get some observations, it became necessary for one man to stand by with an alcohol swab to keep the prism and horizon-cover free from frost. In other cases, a baffle-box was constructed around the front optical parts of the instrument and it was found that this box caught most of the moisture before it could become deposited upon the instrument.

In tropical areas, a similar condition obtains due to the condensation of moisture upon the optical parts of the instrument. It has been found that, again, the baffle-box provides the best means of protection against this nuisance.

One serious limitation of the instrument became apparent soon after it was put into use. This arises from the fact that a partially cloudy condition may render it extremely difficult to make an observation since all stars are observed at an equal altitude and it is usually necessary to set up an observation-list on the basis of local sidereal time prior to the actual observation. It is usually not possible to observe stars at random through holes in an overcast as would be possible with a theodolite or other instrument which was adaptable to stars at any altitude. However, this factor has not been found too limiting since, for the most part, there is usually some period during the night when a considerable portion of the sky is free of clouds. A complete overcast would render any instrument unusable. It is felt that the increased accuracy of the instrument outweighs this slight limitation.

It has been found in practice that the most likely source of inaccuracy in observations arises from the factor of time. A constant check upon watches or chronometer which are used for this work must be made, and under very adverse field-conditions this is sometimes difficult. In some areas, radio fade-outs are common and it is not possible to check timepieces against time-signals constantly. When this happens, it becomes necessary for the party to stand by at the station until an adequate comparison can be made against a signal. Time is the weakest link in the chain of observational procedure and has to be guarded assiduously.

Modifications of the instrument have been made from time to time as field-experience indicated they were needed. The matter of a satisfactory mercury-dish for the artificial horizon has been found to give considerable trouble. At first, rhodium plating on a stainless-steel base was tried, but in time the plating worked free from the steel base and these horizons had to be replaced with ones which had bronze or copper inserts. Copper, which amalgamates freely with mercury, has been found to be the best metal for the dishes, but it offers difficulties since it is not easily machined or worked. On the original instrument the turret-mount for shifting from the low-power to high-power oculars was found inadequate under field-conditions. It has been replaced in the later models by an optical switch which makes it possible, by a flick of the finger, to change from the low power, which is used to find the star being observed, to the high power when the star reaches the edge of the high-power field. All timings of star-crossings are made in the 100-power field. Since the two star-images are traveling in opposite directions, this gives a relative speed of 200 power when compared to instruments where the star-image would be crossing a fixed cross-hair.

The simplicity of operation and the high order of accuracy obtainable with the Equi-Angulator make it an ideal instrument for field-use. It is easy to train personnel quickly and the possibility of any part of the instrument getting out of order under hard field-usage is negligible. It is felt that, for small parties operating under difficult conditions where weight and speed are a prime consideration, this instrument has much to recommend it over previous instruments for latitude- and longitude-determinations.

100 Court Street,
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ABSOLUTE GRAVITY-DETERMINATIONS

Hugh L. Dryden

The National Research Council Committee on Fundamental Physical Constants recently appointed a Subcommittee on Gravity to study the various determinations of the absolute value of gravity and to recommend a "best" value. This Committee consists of E. A. Eckhardt, W. D. Lambert, A. H. Miller, A. Romberg, and the author.

The Committee found only three determinations which had been made with sufficient care and attention to the elimination of systematic errors to merit consideration. These are:

(1) Bestimmung der absoluten Grösse der Schwerkraft zu Potsdam mit Reversionspendeln, by F. Kühnen and Ph. Furtwängler, Veröffentlichung des Königlichen Preussischen Geodätischen Institutes, No. 27, Berlin, 1906. This determination was made in the pendulum-room of the Geodetic Institute at Potsdam, a room on the ground floor about 6 by 6 by 5 meters enclosed in masonry walls one meter in thickness. The pendulums were mounted on an iron casting on two piers in the northeast corner of the room. The geographical coordinates of this station are 52° 22′.86 north, 13°04′.06 east, 87.48 meters above mean sea-level.

(2) The value of gravity at Washington, by Paul R. Heyl and Guy S. Cook, Journal of Research of the National Bureau of Standards, v. 17, p. 805, 1936. This determination was made in the south room of the constant-temperature vault located below the East Building of the National Bureau of Standards, the floor being about eight meters below ground. The pendulum was mounted on the east wall of the room as shown in Figure 6 of the paper. The geographical coordinates of the station are 38° 56′ 30″.143 north, 77° 03′ 56″.893 west, and the floor is 94.75 meters above mean sea-level.

(3) An absolute determination of the acceleration due to gravity, by J. S. Clark, Philosophical Transactions of the Royal Society of London, v. 238A, p. 65, 1939. This determination was made in Room 11 of the Metrology Department of the National Physical Laboratory, Teddington. The pendulum was mounted in an iron casting resting on a concrete pier which extended some five feet down to earth below floor-level. The geographical coordinates of the station are 51° 25′ 14″ north, 0° 20′ 21″ west, 10 meters above mean sea-level.

The values of absolute gravity obtained at these stations were:

(1) Potsdam, K and F	981.274 gals
(2) Washington, H and C	980.080
(3) Teddington, Clark	981.1815

In order to make a comparison between these values, it is necessary to consider the various determinations of the relative values of gravity at Potsdam, Washington, and Teddington. Adopting the results of a study made by W. D. Lambert for the Committee, the following values of absolute gravity are obtained, all referred to the National Bureau of Standards 1936 gravity-station at Washington:

(1) K and F	980.100^0 gals
(2) H and C	980.080^0
(3) Clark	980.084^6

The last two are in approximate agreement, whereas the Potsdam determination is high.

In connection with the editorial review of the paper by Heyl and Cook, the author made a reexamination of the Potsdam determination. The result has been published in Research Paper 1502 of the National Bureau of Standards entitled "A reexamination of the Potsdam absolute determination of gravity." It was concluded that the Potsdam value should be reduced by at least 11 parts per million.

The Potsdam investigators reduced their numerous observations to give 40 mean values which were considered to have equal weight. These values, expressed in terms of the length of a seconds pendulum, ranged from 9941817 to 9942373 $\times 10^{-7}$ m, the maximum difference being 56 parts per million. The 40 values were subjected to a least-squares adjustment intended to correct for systematic errors arising from the deformation of the knife edges and planes, and other departures from the assumed conditions of infinitely small frictionless swinging of the pendulum

about a fixed axis of rotation. This adjustment yielded a value of 9942380 $\times 10^{-7}$ m, higher than any one of the 40 values. It is believed that the observations were not sufficiently numerous and accurate to determine the magnitude of the systematic errors in this manner.

The Subcommittee suggested the value g = 980.083° as the "best" value for gravity at the NBS 1936 station. This value is 17 parts per million less than the value in the Potsdam system.

What is really needed is another independent and accurate method of determining gravity so that information could be obtained as to the systematic errors present in measurements with reversible pendulums. Under present world conditions, however, this problem must await more normal times.

National Bureau of Standards,
Washington, D. C.

RECENT PROGRESS IN GEODETIC SURVEYS OF THE UNITED STATES COAST AND GEODETIC SURVEY

H. W. Hemple

During the past year, the field-survey work of the Division of Geodesy has been accomplished entirely for the military forces. Most of the surveys executed are to locate monuments to serve as control-points for the mapping being accomplished in certain strategic areas in connection with the War Department mapping program. We have also provided the control for surveying and mapping at several of the outlying bases recently acquired by the United States. Control has also been established for the Coast Artillery Corps of the Army at a number of their posts located along the coast.

The specifications for control for the War Department mapping program require that at least one bench-mark and one horizontal control-point be located in each 7-1/2 minute quadrangle. In general, our plan for establishing control in strategic areas has been to place several bench-marks and at least one, and in most instances more than one, horizontal control-station in each quadrangle.

Figure 1 shows the leveling net of the United States as of March 1, 1943. We have had four large level-parties operating during the past year, each party consisting of from three to six leveling units. In the priority mapping areas, we have executed area-leveling, that is, level-lines have been extended over most all of the accessible highways. Leveling work has been accomplished in all the New England States, the States bordering on the Atlantic Seaboard, the Gulf Coast States, and in Oregon and California.

The leveling work for the mapping program is done with specifications to attain second-order accuracy. The lines are single-run with a precise level, and checks between established bench-marks must be no greater than 8.4 mm $\sqrt{K}$, where K represents the distance run between the established marks in kilometers. Bench-marks are set on an average of a mile apart along the line of leveling. The distances between back and foresights are made equal, and in general the same observing procedure is followed as in first-order leveling except that the line is single- instead of double-run.

The triangulation-net of the United States as of March 31, 1943, is shown in Figure 2. All of our work in the continental United States during the past year has been within 200 miles of the coast or international boundary lines. During the past year, we have operated four triangulation parties in the Eastern States, using the portable steel towers and working in New York, Vermont, Maine, Pennsylvania, New Jersey, Maryland, Virginia, North Carolina, Alabama, and Texas. In the west, two mountain triangulation-parties have operated in Washington, Oregon, and California.

Our instructions to the triangulation-parties are that whenever possible the survey-monuments be established near crossroads or points easily identifiable on air-photographs and that ties be made to such objects. In addition, wherever possible, we attempt to locate prominent objects such as water-tanks, church steeples, and points of a similar nature, which appear on the air-photographs. Connections are also provided wherever possible to survey-monuments established by other organizations such as those of the Geological Survey, the Soil Conservation Service, the Tennessee Valley Authority, etc.

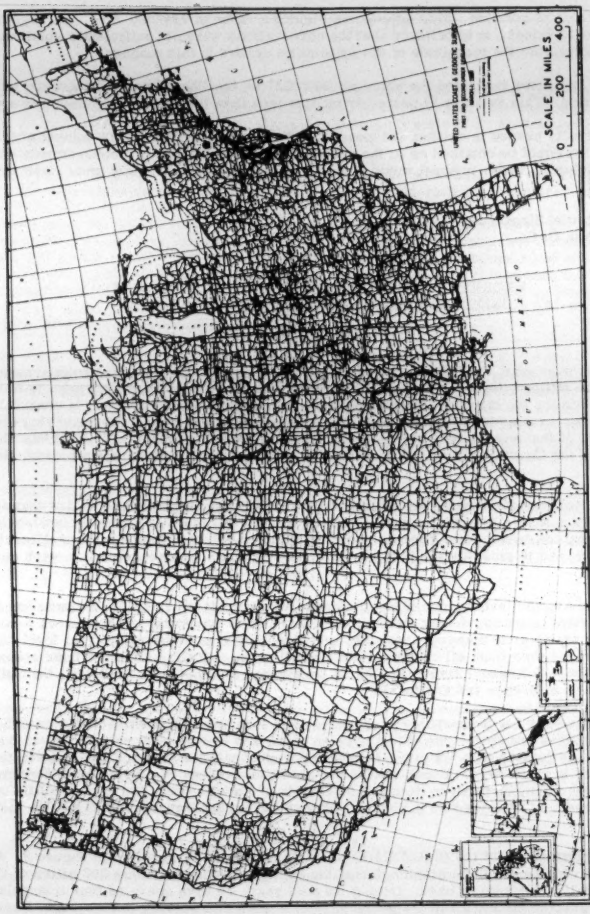

Fig. 1--First- and second-order leveling-net of United States, March 1, 1943

Our specifications for the triangulation in the mapping areas are to attain at least second-order accuracy, that is, a check between base-lines of at least one to 10,000 and triangle-closures not to exceed an average of three seconds or a maximum in any one triangle of five seconds. On these triangulation-surveys we follow the same observing procedure as for first-order triangulation, that is, observations are made at night on electric signal-lamps, and we observe 16 positions with a first-order theodolite on each station to be located. We accept individual positions on any observed direction which do not deviate from the mean in excess of five seconds. These requirements are less exact than those for first-order triangulation where pointings differing by more than four seconds from the mean of 16 positions are reobserved and where the average triangle-

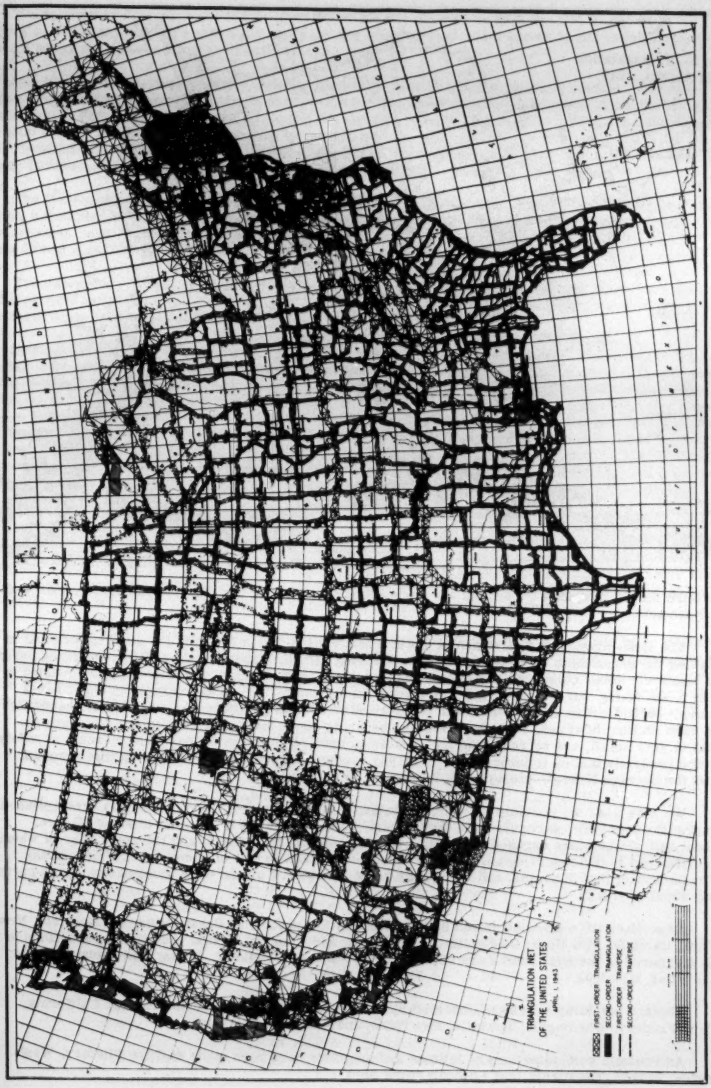

Fig. 2--Triangulation-net of United States, April 1, 1943

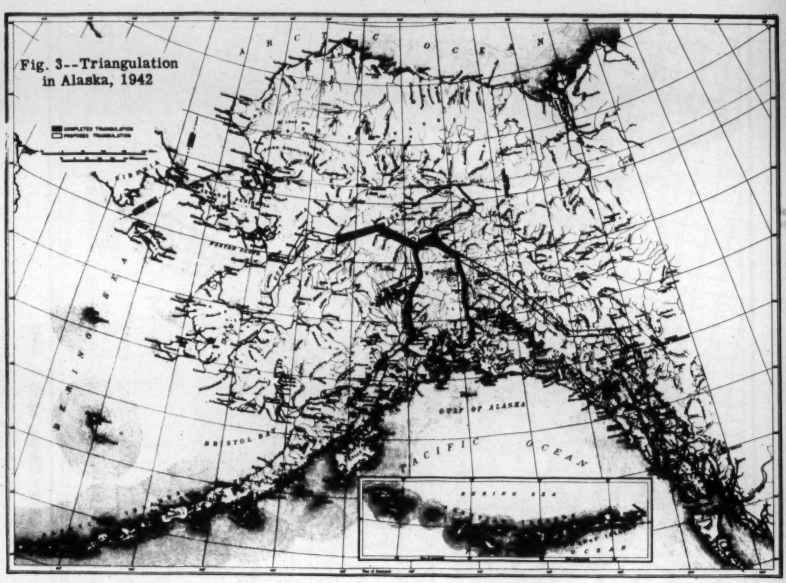

Fig. 3--Triangulation in Alaska, 1942

closure must not exceed 1.0 second and the maximum closure in any one triangle must not exceed 3.0 seconds.

The time-consuming operations in tower-triangulation are in erecting the steel towers and in placing the monuments. The time spent in observing and the station-routine of the observing party is relatively small compared to the erection-program. For example, the tower may be erected in five to six hours, but the observing at a station can be completed, on an average, in about 1-1/2 hours. Second-order observations can be obtained with eight positions of a first-order theodolite on each station; however, the time saved by observing eight, instead of 16, positions on each object is very small, and by requiring the greater number of pointings we establish a factor of safety which generally makes it unnecessary to do any reobserving. We find in following this program that the average triangle-closure will be about 1.25 seconds.

We have used the portable steel triangulation-tower on most of the triangulation accomplished during the past year, particularly in the Eastern States. Each party consists of about 40 men, about half of whom are engaged in erecting and dismantling the towers, and the remainder of whom are attached to the observing units or are assigned to office duties of computing and accounting. The personnel live in camps, and move once or twice a month as the work progresses. Each party has about 18 trucks.

Base-lines have been measured by the triangulation-parties at Bandon, Oregon; Gabriels, New York; Carlisle, New York; Colchester, Connecticut; and Houston, Texas. Additional base-lines to be measured in the near future are those at Troy, Alabama; Yoakum, Texas; San Antonio, Texas; and Flint, Michigan.

Laplace azimuths have been observed by the triangulation-parties near Eureka, California; Cape Flattery, Washington; Lowville, New York; and Anderson, Alabama.

Astronomic determinations of latitude and longitude have been made at Cape Flattery, Washington; Eureka, California; and Lowville, New York.

The triangulation completed in the interior of Alaska during the past season is shown in Figure 3. Also shown is the proposed work for the coming year. Not shown is the triangulation-control along the coast and in southeast Alaska.

One triangulation-party and one astronomic party operated in Alaska last season. The triangulation-party of 33 men completed observations along the Richardson Highway from the Alaskan Range to Fairbanks and thence along the Alaska Railroad to Broad Pass. This arc completed the loop from Valdez through Fairbanks to Anchorage. In addition, an arc was extended from the vicinity of Nenana on the Alaska Railroad westward to Tanana at the junction of the Tanana and Yukon Rivers and thence along the latter to Ruby, Alaska.

The field-computations show the check in position from Valdez to Broad Pass by way of Fairbanks, a distance of 418 miles, to be 0.205 seconds in latitude, 0.033 seconds in longitude, and 3.84 seconds in azimuth. There are 287 main scheme triangles with an average closure of 1.24 seconds and a maximum of 3.84 seconds.

The astronomic party in Alaska observed latitude, longitude, and azimuth at seven stations and longitude and azimuth at one station. The results of this work and a comparison with geodetic positions from the field-computations are shown in Table 1.

During the next season we expect to have one triangulation-party along the Yukon River extending the arc from Ruby to Unalakleet on Norton Sound. Two triangulation-parties will operate in the Yukon Territory from White Pass, where a connection will be made to established triangulation on the north American Datum of 1927 to Whitehorse, thence along the Alaska Military Highway to Big Delta, where a connection will be made to established work on the Valdez Datum along the Richardson Highway. One astronomic party will operate along this section also. The reconnaissance from Ruby to Unalakleet was completed last year. Preliminary aeroplane reconnaissance from White Pass to the International Boundary along longitude 141° 00′ has been completed by officers of the Geodetic Service of Canada. Verification of this proposed scheme by actual ground reconnaissance will be made by our own field-men.

For the arc from Ruby to Unalakleet, we will use aeroplane transportation. Along the Alaska Military Highway, we will depend on transportation by truck. In using aeroplanes, the men and equipment are landed on nearby lakes or rivers, from which they back-pack supplies to their station. Along the highway, the trucks take the personnel as close as possible to the location of their stations, and for the remainder of the distance the supplies are back-packed.

Along some of the sections of the Richardson Highway and also along the Alaska Military Highway, the scheme adopted has figures longer along the axis of progress than normal thereto. This has been the type of figure adopted along narrow valleys so as to have the stations easily accessible to the main artery of travel. The strength of figure for a narrow quadrilateral of this kind is larger and necessitates the inclusion of more frequent base-sites along the arc than where the figure is longer

Table 1--Astronomical results, Alaska, 1942

Station	Geodetic position	Astron. position	A-G	Probable error
	° ′ ″	° ′ ″	″	″
Valdez	61 07 13.128	61 07 04.62	- 8.51	±0.16
North Base	146 17 15.759	146 17 15.84	+ 0.08	±0.21
Willow Creek	61 50 10.565	61 50 31.75	+21.18	±0.18
South Base	145 14 01.048	145 13 30.56	-30.49	±0.04
Miller	63 25 49.201	63 25 59.59	+10.39	±0.15
North Base	145 47 07.516	145 47 00.26	- 7.26	±0.16
Range Astro.	64 48 50.837	64 48 58.90	+ 8.06	±0.10
	147 39 13.615	147 38 52.42	-21.20	±0.27
Summit Astro.	63 22 32.665	63 22 35.26	+ 2.60	±0.19
	149 01 14.168	149 00 43.40	-30.77	±0.03
Peters East	61 27 58.54	.....	.....	.....
Base	149 22 59.46	149 23 23.68	+24.22	±0.21
Ruby	64 44 26.449	64 44 37.88	+11.43	±0.07
	155 28 36.416	155 28 20.90	-15.52	±0.00
Unalakleet	.....	63 52 30.54	.....	±0.11
	.....	160 47 31.98	.....	±0.16

normal to the axis of progress. In the vicinity of Thompson Pass on the Richardson Highway, base-lines were measured every three to four quadrilaterals in contrast to a base-line every 12 to 15 quadrilaterals under more favorable conditions in a normal scheme of triangulation.

The completion of the arc along the Alaska Military Highway will enable the triangulation of the interior of Alaska and also along the coast of southwest Alaska as far as Wide Bay to be referred to the North American Datum of 1927. With the completion of the work planned for the coming summer, continuous triangulation will then exist from Norton Sound, Alaska, to the southern end of the 98th meridian in Mexico, where it borders on the Pacific Ocean.

The difficulties of operating in the interior of Alaska on triangulation-surveys cannot be minimized. Difficulty of access of stations, inclement weather, and distant sources of supply are major problems, the solution of which requires competent planning and the use of experienced men in order to successfully carry on operations.

The statistics for the work accomplished from April 1, 1942, to March 31, 1943, are given in Table 2. No gravimetric surveys have been accomplished during the past year, and this type of work will not be resumed until after the war.

Table 2--Geodetic work accomplished March 1, 1942, to March 31, 1943

Work	Completed 1942-1943	Total to date
Triangulation, first- and second order	5,170 miles	90,445 miles
Leveling, first- and second-order	24,492 miles	317,040 miles
First-order base-lines	8	233
Second-order base-lines	0	55
Latitude-stations	9	873
Longitude-stations	11	727
Azimuth-stations	11	1,190
Gravity-stations (pendulum)	0	1,130
Gravity-stations (gravimeter)	0	37

The variation-of-latitude observatories at Ukiah, California, and Gaithersburg, Maryland, have continued in operation throughout the year. These are two of five stations located on the same parallel of latitude engaged in a similar observing program. The other observatories are located one each in Russia, Italy, and Japan. The resulting data for this program are used in studies concerning the movement of the Earth's axis.

Practically all of the computation and adjustment of triangulation that has been done during the year has been in defense or critical areas. The processing of the data has been kept up closely behind the field-parties in spite of an unusually large turnover of personnel due to loss of men to the military services. Several women mathematicians have been in training to replace the men during the latter half of the year. Computing offices have been maintained at Philadelphia and New York, using Work Projects Administration personnel until July 15, 1942, and since then with our own personnel selected from registers of the Civil Service Commission. These offices have greatly expedited the geodetic computations of triangulation and leveling and have assisted other divisions of the Coast and Geodetic Survey as well.

The following geodetic publications were printed during the year or are in press at the present time:

Special Publication 232, Pendulum gravity-measurements and isostatic reductions, by CLARENCE H. SWICK
Special Publication 233, Gravity-observations in Peru and Columbia, by CARL I. ASLAKSON and CLARENCE H. SWICK
Special Publication 234, Signal building, by JASPER S. BILBY

The latter publication is concerned with the erection of wooden towers to be used for observational purposes. This is largely a reprint of Section II of our former Special Publication No. 93, "Reconnaissance and signal building." Reconnaissance for triangulation is now treated in Special Publication No. 225, "Manual of triangulation reconnaissance," issued in 1941. During the past year, we have found a demand for the treatise on the building of wooden towers, particularly from the Army, and since Special Publication No. 93 was out of print it was decided to issue a separate

publication devoted to signal-building using timber. It is expected this publication will be issued within the next few weeks.

A large amount of printing has been done by photolithography. Triangulation and leveling data are now issued in this form. Several special coordinate tables for military use, tables in meters for the machine-computation of geographic positions, etc., have also been issued in lithoprint form.

Legislation authorizing the use of the State plane coordinate system in property-descriptions has been under consideration during the past year in the State legislatures of California, Minnesota, and Texas. In Texas the bill has been passed by the State House of Representatives and is now being considered by the State Senate. In California the bill has been passed by the Assembly and is now under consideration by the State Senate. Favorable action appears likely in each of these States. There are now six States having such legislation: New Jersey, Pennsylvania, New York, Maryland, Massachusetts, and North Carolina. Glynn County in Georgia also has comparable legislation.

The National Bureau of Standards has cooperated as in past years by graduating theodolite-circles and by standardizing invar-tapes used in base-measurement and traverse surveys. In return, we have determined a number of distances at the National Bureau of Standards to be used in the calibration of range-finders for the armed forces.

The Naval Observatory and the Naval Communications Service cooperated during the past season by transmitting two special time-signals for use of our astronomical party operating in Alaska. Special time-signal broadcasts will also be transmitted this next season for similar use.

We have made a field-test of the new theodolite reading to one second made by the Gurley Company for the Engineer Board of the United States Army. The results of the test have been furnished to the Gurley Company and to the Engineer Board, together with our conclusions and recommendations for changes.

We are continuing experiments to improve our electric signal-lamps. Our objective is a lamp which will be light, yet sturdy enough to withstand rough usage, and which can be manufactured cheaply and quickly.

Because of the critical shortage of bronze, it has been necessary to specify that a recent order for bench-mark discks be made of malleable iron. Our supply of triangulation, reference, and azimuth-mark disks made of bronze is adequate for the time being, although any order placed in the immediate future for these markers will have to specify that non-critical materials be used.

The difficulties of operating mobile surveying parties in the continental United States during these days of rationing and manpower shortages are considerable. On some of our parties, the turnover in personnel has been as much as 60 per cent. Unit costs have increased, and new standards to determine economical operating conditions will have to be adopted based on the present situation. Insistence primarily is on adherence to specifications so that the resulting surveys will conform to standards of accuracy long in existence. There will be no diminution in our requirements for accurate surveys.

U. S. Coast and Geodetic Survey,
Washington, D. C.

REPORT OF THE GEOGRAPHICAL AND TOPOGRAPHICAL ACTIVITIES IN MEXICO DURING THE YEAR 1942

Manuel Medina

(I) Triangulations

Four geodetic nets were developed in 1942:

(a) The triangulation of the State of Jalisco
(b) The triangulation of the Laguna (Durango-Coahuila)
(c) The connection of the triangulations of the State of Zacatecas and those of the Laguna
(d) The triangulation of the Valley of Guadalajara

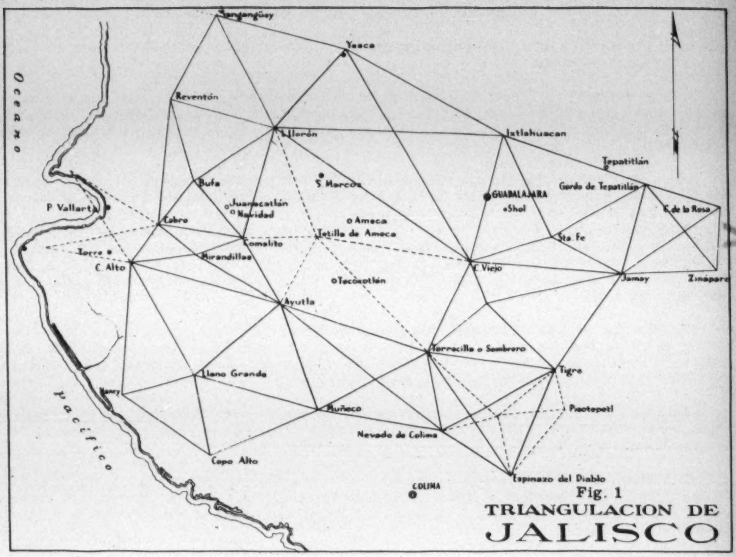

Fig. 1
TRIANGULACION DE
JALISCO

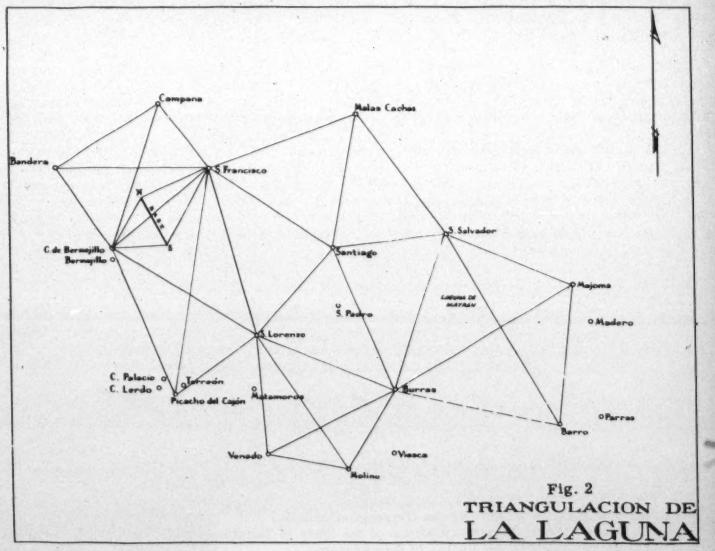

Fig. 2
TRIANGULACION DE
LA LAGUNA

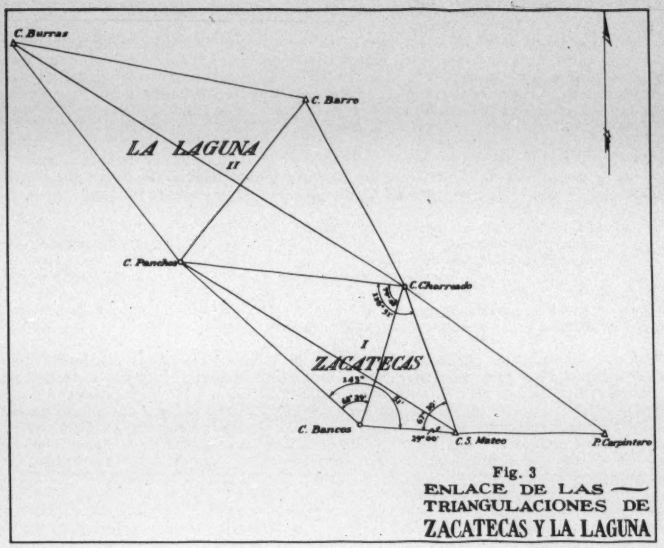

Fig. 3
ENLACE DE LAS TRIANGULACIONES DE
ZACATECAS Y LA LAGUNA

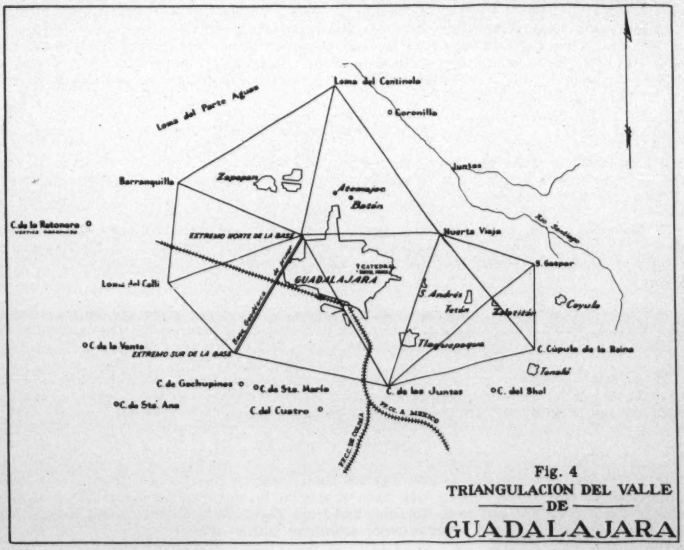

Fig. 4
TRIANGULACION DEL VALLE
DE
GUADALAJARA

The triangulation of Jalisco (see Fig. 1) covers an area of 28,874 square kilometers and consists of 18 geodetic points at which the angles were measured with a "Wild" precise theodolite. This triangulation is the geodetic net on which the topographical surveys in the State of Jalisco are being based. It consists of six primary triangulations tied-in on the Lerma and Santiago River triangulations, by means of the lateral sides Jamay-Cerro Viejo and Llorón-Reventón, and on a base-line eight kilometers long situated in the vicinity of the City of Guadalajara.

Through tying-in with the aforesaid triangulation, it was possible to calculate indirectly the length of the base-line near Guadalajara and compare these data with the result of the direct measurement of said line on the ground. The respective lengths are as follows:

Length of the base-line near Guadalajara as obtained by actual measurement	8,009.731 meters
Calculated length of the same line	8,009.700 meters
Difference	0.011 meter

This small difference represents a relative error of 1:100,000, which speaks highly of the degree of accuracy attained in the geodetic work done in Jalisco.

The main object of the triangulation in the Laguna District was the establishment of geodetically determined fixed triangulation-stations on which the National Irrigation Commission could base its topographical surveys. It covers an area of 9,327 square kilometers, and comprises five geodetic polygons, directly supported by a base-line six kilometers in length, measured near Bermejillo. This triangulation (see Fig. 2) is a part of the triangulation of 26° parallel of latitude, of which system it is to form a unit when the latter has been finally observed. Angles were taken with a "Wild" theodolite, and the geodetic base of Bermejillo was established with two invar-wires 24 meters long.

The interconnection of the Zacatecas and Laguna triangulation-systems, after having been studied and decided upon, was effected by means of two quadrilaterals, by which the extreme northern side of the Zacatecas triangulation-system Cerro Bancos-Cerro San Mateo was joined with the Cerro Burras-Cerro Barro side of the Laguna triangulation-system (see Fig. 3).

The triangulation of the Valley of Guadalajara was measured in order to provide fixed points for the aerial survey of this Valley. A second-order subsidiary triangulation of this Valley was made, supported directly by the geodetic base of Guadalajara. It consists (see Fig. 4) of a hexagon with its central point in the extreme northeastern end of the base-line and of a quadrilateral. It covers 232 square kilometers.

(II) Astronomical positions

At the instance of the Pan American Institute of Geography and History, the geographical positions of the Pacific Ocean ports of Acapulco, in the State of Guerrero, and Guaymas, in the State of Sonora, were determined.

In the observations at the port of Guaymas, a Repsold altazimuth was used; time was determined by the method of equal altitudes of two stars, and latitude by measuring the circummeridian altitudes of stars. The probable error in these determinations were: Latitude $\pm 0''.2$; longitude, $\pm 0''.4$.

At the port of Acapulco, a Repsold zenith instrument was used, observing the meridian passages of stars for the determination of time and following the Horrebow-Talcott method for the finding of latitude. The calculation of this station is in actual process.

In the State of Puebla, complying with a request of the Director of the Astrophysical Observatory of Tonantzintla, the astronomical position of the Observatory was established using the same instrument and methods similar to those employed in Guaymas.

(III) Precise leveling

In accordance with the plan of investigation established by the "Consejo Mixto" for the study of the subsoil of the City of Mexico, new lines of precise levels were run along the great National Drainage Canal from Atzacoalco to Nonoalco and from Tacubaya to the monument of Carlos IV, which stands at the junction of several major downtown traffic-arteries.

(IV) Topographic and phototopographic surveys

As has already been said, some fundamental surveys were made in the Valley of Guadalajara to serve as a base for the aerial surveys of that Valley. The mosaic air-view of the Valley, taken by the "Compañía Mexicana Aerofoto, S. A.", was rigidly based on and adjusted to the topographic triangulation of the Valley and to a polygonal traverse covering the same. The mosaic was satisfactorily finished and exhibited at the Third National Congress of Geography, held in the City of Guadalajara in February, 1942.

In the State of Zacatecas, a map of which has been finished and is soon to be published, polygonal surveys were made of the eastern and southern zones of the State and its topographic details were completed by an aerial survey of the western region of some 10,000 square kilometers.

A terrestrial photogrammetric survey of the mountains surrounding the City of Zacatecas was made for the purpose of a featured plan of that region for further important studies to be undertaken later on.

(V) Geotopographical activities in the States of Puebla and Tamaulipas

With a view to improving the geographical maps of the States of Puebla and Tamaulipas produced by the "Comisión Geográfico Exploradora" and which therefore lack many details of latter dates, topographical surveys were made of that region. These show new highways, buildings of all kinds, and any other salient features which do not appear in the maps of the "Geográfico Exploradora," together with the necessary geodetic points of reference.

(VI) Establishment of the boundaries with the Republic of Guatemala

In accordance with the program of operations as prescribed by the Secretary of Foreign Affairs, the surveying and marking of the boundary line between Mexico and the Republic of Guatemala were continued. These operations were started in December, 1941, and were suspended April 30, 1942, due to arrival of the rainy season, which rendered all work of this kind impossible in that region.

(VII) Mapping activities

In the course of 1942, the originals of the geographical maps of the States of Morelos and Zacatecas were finished to the scales of 1:50,000 and 1:500,000, respectively.

Besides, the 24th edition of the Geographical Atlas of the Republic was issued. It is composed of maps published at different scales, as well as certain explanatory matter which did not appear in former editions. This edition was dedicated to the "Inter-American Congress of Agriculture" held in Mexico City, July, 1942, and comprises the following maps:

General political map of the Republic at	1:5,000,000
Hydrographic map of the Republic at	1:5,000,000
Altimetric map of the Republic at	1:5,000,000
Magnetic map of the Republic at	1:5,000,000
Climatological map of the Republic at	1:5,000,000
Map of communications of the Republic at	1:5,000,000
Map of the soils of the Republic at	1:5,000,000
Geological map of the Republic at	1:5,000,000

and maps of all the States of the Republic, each being accompanied by oro-hydrographic chart and a chart showing its political divisions.

The preparation and publication of this Atlas, in which the maps of States are brought up to date and which show the modern highways as well as data taken from various sources, required editorial effort of some consideration, which culminated in the distribution of this geographical information amongst the members of the Second Pan American Agricultural Congress.

Oficina de Geografía,
Tacubaya, D.F., Mexico

AMERICAN GEOPHYSICAL UNION

TWENTY-FOURTH ANNUAL MEETING

SECTION OF SEISMOLOGY

REPORTS AND PAPERS

Washington, D. C.
April 24, 1943

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ADDITIONAL EVIDENCE FOR HIGH-SPEED SURFACE-WAVES OVER ATLANTIC PATHS

Ralph R. Bodle

For some years seismologists have been collecting data relative to the existence of high-speed surface-waves over Atlantic paths similar to those which have been observed over Pacific paths. In the Atlantic Ocean there has been difficulty in obtaining all ocean paths of sufficient length so that identification of the wave-groups could be accomplished without confusion. The Meteorlogical Service at Bermuda (M. A. Macky in charge), the Woods Hole Oceanographic Institution, and the United States Coast and Geodetic Survey arranged jointly to have a seismograph installed at St. Georges, Bermuda, in 1939. This was done with the hope that enough data might be accumulated so that more definite conclusions might be drawn. The earthquakes of November 10 and 28, 1942 (see Fig. 1), gave good results in that the high-speed (Love) waves are clear and well defined for an Atlantic path. They indicate an average speed of about 4.5 km/sec.

The shock of November 10, 1942, is exceptional in that the epicentral distance is greater than any observed since establishment of the Bermuda station--13,230 km (8,200 miles) from a point about 1,500 miles southeast of Capetown, South Africa. The rate of travel in this case was very near, or may have reached, the upper limit for transverse surface-waves--4.67 km/sec. It is considered that these records add strong evidence on the existence of high-speed surface-waves for Atlantic paths.

Having obtained these data, the writer became interested to learn whether waves of this type were transmitted over other paths. Accordingly, data for a number of stations were tabulated. It will be interesting to note the following data given in Table 1:

(1) A rate of 4.64 km/sec was found for a 50 per cent land-route from the Celebes Sea to Scoresbysund, some 12,000 km (January 5, 1941).

(2) A rate of 4.57 km/sec was found over an 80 per cent land-route from Iran to Scoresbysund (February 16, 1941).

(3) A rate of 4.67 km/sec was found for a route from Cyprus to Scoresbysund--a broken water-route over Europe, North Sea, and Arctic Ocean (March 16, 1941).

(4) A rate of 4.47 km/sec was found for a route from Mexico over the Gulf of Mexico to Bermuda (February 11, 1941).

(5) There were two instances where the high-speed waves were not observed over Atlantic paths (March 16 and 21, 1941).

The tabulations indicate that the high-velocity surface-waves may be observed over routes which are largely land; also that they may be missing for some Atlantic paths, though the latter evidence is weak. These observations lead to a number of questions among which are:

(a) Does the intensity of an earthquake influence the generation of high-speed surface-waves?

(b) Does the variation of focal depth in the upper layers influence the generation of high-speed waves?

(c) May we assume that high-speed waves are present but greatly modified by the overburden of continental layers?

(d) Does the nature of displacement at the focus influence the formation of high-speed surface-waves?

Answers to the questions are not discussed here. Data accumulated by a very brief investigation brought the questions to mind and it seemed desirable that they be mentioned so they might be considered with the data of Table 1.

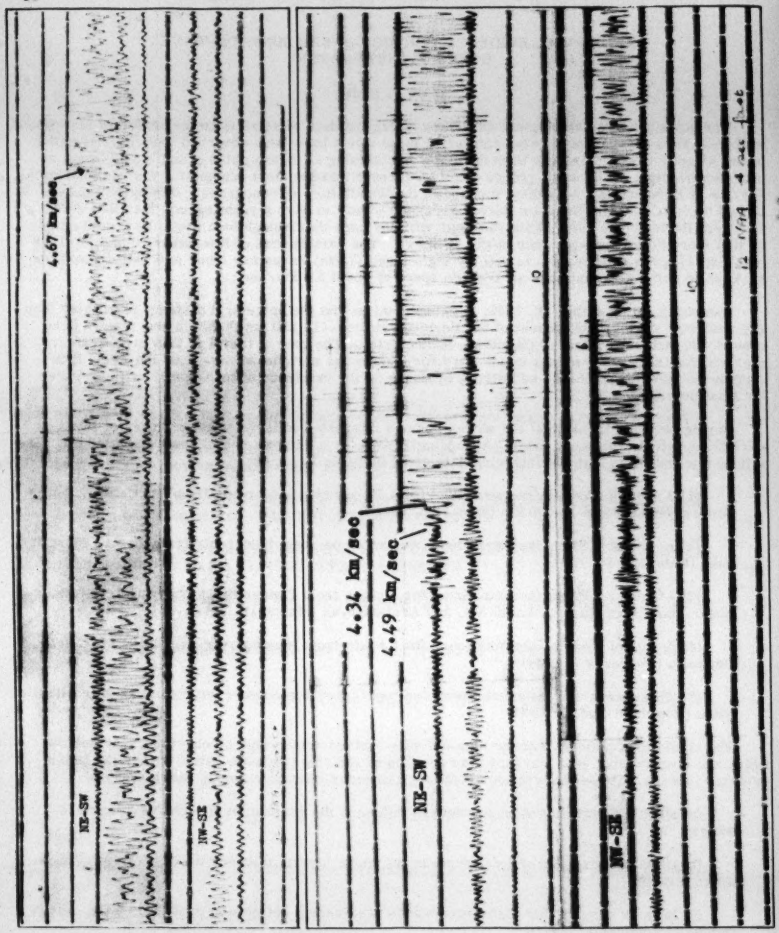


Fig. 1--Records of Bermuda earthquakes
Left: November 10, 1942 (H = $11^h\ 41.3^m$ GCT; epicenter, 46°.5 south and 35° east; azimuth, south 42° east; Δ = 13,230 km)
Right: November 28, 1942 (H = $10^h\ 38.8^m$ GCT; epicenter, 7°.3 north and 36°.8 west; azimuth, south 52° east; Δ = 4000 km)

Table 1--Summary of data on earthquakes involving high-speed surface-waves over Atlantic Ocean

Date	GMT	Epicenter Lat.	Epicenter Long.	Distance	Component	Azimuth from sta.	Rate	Remarks re path
1941	h	°	°	km		°	km/s	
					Bermuda[b]			
Feb. 11	14	15.4 N	94.7 W	3,565	NE	S 65 W	4.43	50 per cent water, very broken;
					NW		4.47	Gulf of Mexico and Atlantic
Mar. 16	7	49.9 N	157.2 E	9,970	NE	N 24 W	3.35	All land via Alaska and Canada
					NW	.....	.....[a]	
16	16	37.9 N	12.5 E	6,835	NE	N 61 E	3.60	90 per cent water, Europe and
					NW	.....	.....[a]	Atlantic
21	7	6.9 N	34.4 W	2,995	NE	S 64 E	3.17	All water, Atlantic
					NW	.....	.....[a]	
28	22	(30) S	(178) W	10,140	NE	S 73 W	2.88	80 per cent water, Pacific and
					NW	.....	2.64	United States; very weak records
Apr. 13	7	3 S	13 W	6,680	NE	S 76 E	4.62	44 per cent water, Atlantic; de-
25	22	14.5 S	75.5 W	5,333	NE	S 17 W	4.63	structive in Peru
Sep. 26	4	12.8 N	87.5 W	3,190	NE	S 51 W	4.02	Pacific coast of Nicaragua; 78 per cent water, Gulf of Mexico and Atlantic
Nov. 10	11	46.5 S	35 E	13,230	NE	S 50 E	4.67	All Atlantic
28	10	7.3 N	36.8 W	4,000	NE	S 50 E	4.34	All Atlantic
					NE	S 50 E	4.49	
					Burlington			
Nov. 28	10	7.3 N	36.8 W	5,420	NW	S 48 W	4.29	85 per cent Atlantic
					NE	.....	4.93	
					Huancayo[c]			
Nov. 10	11	46.5 S	35 E	10,540	NS	S 42 E	4.40	68 per cent Atlantic
					Philadelphia[c]			
Nov. 28	10	7.3 N	36.8 W	5,255	NS	S 58 E	4.04	All Atlantic
					Scoresbysund			
Jan. 5	18	2.1 N	122.9 E	12,000	EW	N 35 E	4.64	50 per cent water, China Sea, Asia, Arctic Ocean
20	18	35.2 N	33.8 E	5,110	EW	S 81 E	3.92	29 per cent water, Europe, Arctic Ocean; focal depth about 100 km
Feb. 16	16	33.5 N	58.5 E	6,220	EW	N 89 E	4.57	20 per cent Arctic Ocean; de-
11	14	15.4 N	94.7 W	7,750	EW	S 80 W	4.12	structive in Iran 27 per cent Gulf of Tehuantepec, Gulf of Mexico, Davis Strait
Mar. 16	7	49.9 N	157.2 E	6,620	EW	N 1 E	.....[a]	Kamchatka, Siberia, and Arctic Ocean; focal depth about 150 km
16	16	37.9 N	12.5 E	4,130	EW	S 48 E	4.67	About 75 per cent water, very broken; France, North Sea, Arctic Ocean; focal depth about 100 km
21	8	6.9 N	34.4 W	7,120	EW	S 15 W	4.56	All Atlantic
28	22	30 S	178 W	14,150	EW	N 28 W	4.07	Pacific via Kodiak, Alaska, and Canada; focal depth possibly 100 km
					Huancayo			
Mar. 21	8	6.9 N	34.4 W	4,980	EW	N 67 E	3.92	32 per cent Atlantic
					San Juan			
Mar. 21	8	6.9 N	34.4 W	3,660	EW	S 74 E	.....	All water; surface-waves not well defined
					Tucson			
Mar. 21	8	6.9 N	34.4 W	8,316	EW	S 89 E	3.90	62 per cent Atlantic

[a]No record surface-waves. [b]Recording station on island. [c]Recording station on mainland.

U. S. Coast and Geodetic Survey,
Washington, D. C.

THE NON-INVARIANTIVE CHARACTER OF THE ISO-p SURFACE AS AN ISO-P SURFACE IN THE STATISTICAL INTERPRETATION OF GEOPHYSICAL DATA

Archie Blake

(Abstract)

Uncertainty affecting the estimation of prior probabilities has led to the growth of a school which evades the difficulty by setting up a definition of the class of "significant" observations in which the prior probability does not appear.

The purpose of this paper is to state one of the objections to this method. For concreteness let the likelihood or inverse probability p of an observation be defined on a three-dimensional space. We seek to define a surface which shall divide the points of this space into two subclasses, the significant and the insignificant. Part of the definition of the surface is that the integral of p over the significant points shall have a prescribed value, P; we therefore call the surface an iso-P surface.

This condition on the integral over the significant region is far from enough to determine the surface--and this is true even in one dimension. One proposal frequently used--often tacitly--is to define the iso-P surface as coinciding with an iso-p surface which cuts off the desired integral P. This procedure removes the chief ambiguity, but is open to a serious objection.

A valid method must yield results unaffected by arbitrary matters such as the coordinate system chosen to study the data. It is evident, however, that we can transform our variables in such a way that the space will be compressed or attenuated from one locality to another so that the iso-p surfaces will assume very different shapes, and, in particular, will not coincide with the transforms of the iso-P surfaces initially defined in terms of them. The method, therefore, does not meet the requirement of invariance.

This requirement is met by the method of inverse probability. Bayes' formula for the probability of a hypothesis du after an observation v may be written

$$du^{v} \propto v^{u}\, du \qquad (1)$$

the presence of a superscript or dot indicating that a probability is meant instead of a value or differential of u or v. (This notation reduces the cluttering up of the formula with unimportant symbols.) We have $p = v^{u}$; also

$$du \cdot = f(u)\, du \qquad (2)$$

The loss of invariance in the method of likelihood or fiducial probability is due to the unjustified suppression of the factor f(u). [We note that there exist variables for which f(u) is constant and the method yields correct results.]

In actual application, the deficiency is mitigated by the use of prior considerations in choosing the statistics u to be studied and by the fact that the prior probability decreases in importance for large samples. Despite this, there are many important problems in which an explicit treatment of the prior probability would greatly improve matters. For example, it would help free the subject from the (not wholly unjustified) reputation that "you can prove anything by statistics," which arises in part from abuse of the freedom to choose the statistic for which P is computed. A device used to compensate for this freedom, of insisting on a very low value of P before a result is adjudged significant, is itself a very costly procedure; it must entail the throwing away of many leads that might have proved profitable. The method of inverse probability is at least free from these two objections--its results do not depend on the choice of statistics. To put the case in another way, we cannot obtain results uninfluenced by the prior probability, since our choice of statistics depends on it; let us, therefore, bring that slippery customer out into the open and make him appear explicitly in our formulas, where we can clearly see what influence he is exerting on our conclusions.

Washington, D. C.

THE EXPONENTIAL LAW OF GRAVITATION AND ITS EFFECTS ON SEISMOLOGICAL AND TECTONIC PHENOMENA: A PRELIMINARY EXPOSITION

Anatol James Shneiderov

Introduction

The purpose of this paper, as its title indicates, is to show a possible application of the newly developed exponential formula of gravitation to the solution of certain geophysical problems. Among these problems are those dealing with the epeirogenic and orogenic movements of the Earth's crust in general, together with several particular aspects of these two great phenomena, for example, periodicity of mountain-building, parallelism in oppositely situated coasts, "swelling" of ocean-beds, concentration of earthquake occurrences in the regions of recent and present-day mountain development, glacial periods, and also an allied astronomical problem--the explanation of the variations in the length of the day.

Several solutions of these problems have been proposed since Suess's "The face of the Earth" appeared in print in 1885. Among recent theories, those of Kober's Theory of geosynclinal orogen, Wegener's Theory of continental drift, Daly's Sliding continents, and Holme's Convection-current theory all make some contribution toward accounting for the above-mentioned phenomena.

"A satisfactory theory of physical phenomena need not necessarily attempt to explain the observed phenomena on any 'cause and effect' basis. However, a correspondence between the elements and the structure of the theory with those of the observed physical world seems called for. For, the value of the theory is largely determined by its predictive properties, and these must certainly depend upon such a correspondence." [Quoted from a letter from J. H. Taylor of George Washington University to the author.]

In agreement with this statement, there will be presented here (1) a set of physical-mathematical postulates corresponding in their elements and structure, and (2) a certain set of mathematical formulas corresponding to observed phenomena and predictable facts.

Newtonian-LeSagian formula of gravitation

Newton's empirical formula of gravitation is a simple and precise one, extensively proved by experimental and observational evidence, so far as the problems of the external field are concerned, that is, those of gravitational interaction between two material bodies outside of each other. However, the situation becomes uncertain, and even obscure, when the question arises as to whether the Newtonian law of gravitation holds true in the interior of bodies, for example, in the interior of the Earth.

Apart from the complications involved due to the non-homogeneity of the Earth, the main difficulty in an experimental verification of the Newtonian law of gravity within the Earth lies in the inaccessibility of its interior for the purpose of a direct and accurate measurement of its gravity force. Some information concerning the Earth's constitution may be gained through the channels of seismology and celestial mechanics; neither of these can provide us, however, with more than a rough picture of gravitational force inside the Earth.

An inference of the Newtonian law of gravitation is that gravity at corresponding points of two homologous spheres is proportional to the ratio of their radii, but this inference has never been experimentally or observationally proved to be correct. Thus, there is no direct experimental evidence nor direct observation which would permit one to assert that the Newtonian formula of gravitation is correct, simple, and precise for the internal field, as it has proved for the external field.

In Figure 1 the precise and simple Newtonian gravitational formulas are given. The formula above and between the two spheres is the one for the external field. The dotted brace shows the distance R between the centers of the two spherical masses, m and m_1. The symbol f_N indicates the Newtonian gravitational force which attracts or "pulls" one body toward another. G indicates the gravitational constant, and δ the density in grams/cc.

To the right of the lower sphere, the Newtonian gravitational formula for the internal field is given. Small arrows indicate that the attraction of the material point m_1 is directed at the center of the sphere m, while the formula shows that f_N in this case is proportional to the distance R. Vectors of gravitational force are attached to the centers of the masses in the conventional way--"heads out," signifying a pull.

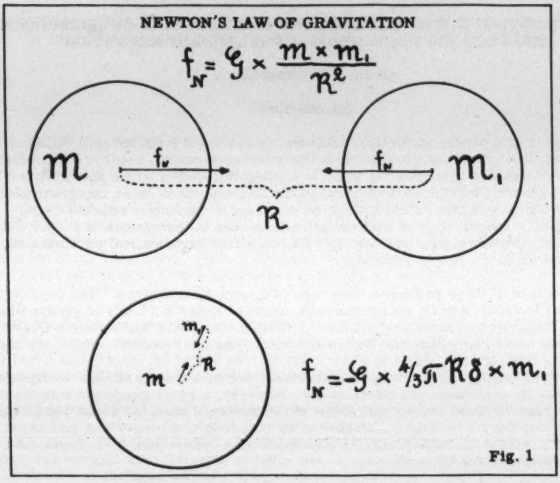


Fig. 1

The nature of gravitation remains unexplained, except by the general theory of relativity which, however, is not yet completed. Newton's statement, hypothesis non fingo, did not prevent him from using one hypothesis, namely, that of actio in distans. "Newton held attraction at a distance an essential property of matter, thus introducing an occult quantity," wrote one of his immediate post-contemporaries.

Scientific thought could not then, as it cannot now, be reconciled with this action at a distance, as it must be considered highly unnatural for one body to act upon another without being in contact with it, either directly or indirectly, through a medium.

Later, when astronomy and physics began to accumulate more and more facts, triumphantly claiming the correctness and precision of the Newtonian formula of gravitation, scientists started concentrating their efforts on research in the nature of gravitation.

Among many futile attempts along this line, there was one made by LeSage of Geneva which happened to be futile only by accident, that is to say, Robert Meyer, Joul, and Helmholtz, the formulators of the law of conservation of energy, were not born until long after LeSage produced his theory of gravitation. Because of this "accident", LeSage was handicapped by not realizing that he should have taken into consideration the conservation of energy.

It was while the author of this paper was independently developing his own theory of the exponential law of gravitation that he had brought to his attention the LeSagian theory of gravitation. A contemporary of President Jefferson, LeSage of Geneva published his paper on gravitation in the Memoirs of the Berlin Academy, in the year 1784. At that time, the corpuscular theory of light was universally accepted, while the kinetic theory of gases was still far beyond the scientific horizon. But the genius of LeSage made him grasp correctly the general idea of the nature of gravitation. The following is a short description of LeSage's idea given in the words of a noted English physicist, P. G. Tait:

"How, then, is gravitation to be accounted for?" asked Professor Tait in one of his lectures. "Any theory," he continued, "must be rejected at once if it can be shown to be incapable of explaining this grand law of nature, which tells us that every particle or atom in the universe attracts every other with a force proportional to their masses conjointly, and to the square of their distance inversely.

"Now the only plausible answer to this which has yet been expounded, was given long ago by LeSage of Geneva. He showed that gravitation can in all cases be accounted for by the supposition

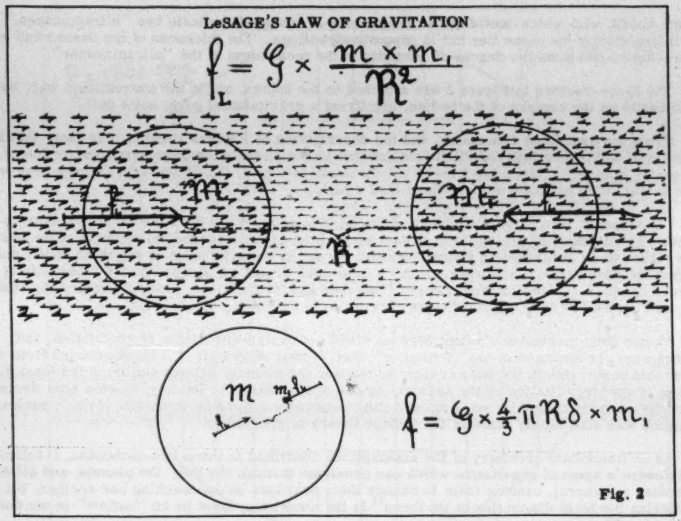


Fig. 2

that in addition to the grosser particles which are the atoms of tangible or sensible matter, infinite as they are in number, there is an infinitely greater number of much smaller ones darting about [or streaming] in all directions with enormously great velocities. Lesage showed, if this were the case, the effect of their impacts upon the grosser particles or atoms of matter would be to make each two of these behave as if they were attracted to one another with a force following exactly the law of gravity.

"In fact, when two such particles are placed at a distance from one another, each screens the other from the part of the shower which would otherwise batter upon it. If you have a single lone particle, it would be equally battered on all sides, but when you bring in a second particle, it screens the first to a certain extent, in the line joining the two; and the first in turn screens the second, so that, on the whole, each of these two is battered more on the side opposite to the other one; and, therefore, there is a tendency to bring the two together by the excess of battering outside over the inside. Now it is a very easy mathematical deduction to show that the result of this is equivalent to an attraction inversely as the square of the distance; and, therefore, that it exactly agrees with the law of gravity.

"It is necessary also to suppose that particles and masses of matter have a cage-like form [the rods of the cage being incomparably smaller than the intervals between them] so that enormously more corpuscles pass through them than impinge upon them, else the gravitation action between two bodies would not be a product of their masses [or of their contents of matter, if mass is considered to be proportional to the contents of matter]." [Quotation from P. G. Tait, Lectures on some recent advances in physical science, 1876, MacMillan and Co., London; the explanations in brackets are introduced by the author of this paper.]

In Figure 2 the LeSagian gravitational force which numerically and functionally is identical with the Newtonian force of gravitation, is indicated by f_L. The part of the stream of the LeSagian ultramundane which traverses the spherical body of the mass m_1, from the right, is partially intercepted by the cage-structure of the interior of the sphere. Therefore, the pressure of this stream on the body m is weaker than the pressure of the opposite stream, from the left, which traverses the sphere m without having been previously intercepted by another body, thus acting on the cage-structure of the sphere m with full strength. As a consequence of the two oppositely directed and unequal pressures on the structure of the body m, a force f_L results, which pushes the sphere m toward the sphere m_1. By an exactly similar process the sphere m_1 is pushed toward the body m. And this is the essence of LeSage's idea of gravitational "attraction." The two semi-

arrow-heads, with which each dash in the drawing is equipped, indicate two "ultramundane," moving in practically the same line but in opposite directions. The thickness of the dashes and semi-arrow-heads indicates the degree of intensity in the momentum of the "ultramundane".

The force-vectors in Figure 2 are attached to the bodies, not in the conventional way, but with their heads on the centers of the bodies, signifying a gravitational push, not a pull.

From the preceding discussion, and the descriptions of Figures 1 and 2, it is clear that the substantial difference between the Newtonian and LeSagian theories of gravitational action is in the modus operandi. While the first is an attraction or a pull, the second is a definite push which is to be regarded as much more natural than a pull.

"It seems to be a natural tendency of the mind to account for the unknown cause of an attraction by calling it a pull, while in those cases which we have learned to understand we find that it is rather to be described as a push. When a horse, as we say, 'pulls' a wagon he really pushes against the horse collar; and when we pull a door shut we put our fingers on the other side of the knob and push." [Quotation from Lodge, The ether and its functions, Nature, January 25, 1883, p. 305, as requoted by P. R. Heyl, What is gravitation?, Sci. Mon., v. 47, 1938.]

As has been mentioned already, Newton could not explain the nature of gravitation, and, furthermore, he assumed in his "Principia" that "power of gravity ..... must proceed from a cause that penetrates to the very centers of the sun and planets, without suffering the least diminution of its force (italics by the author). In one of his letters to Bentley, Newton also wrote: "Gravity must be caused by some agent acting constantly according to certain laws." Such an assumption was also tacitly made in the LeSage theory of gravitation.

As an immediate corollary of the assumptions contained in these two quotations, it follows that Newton's agent of gravitation which can penetrate through the Sun, the planets, and all material bodies in general, causing them to change their positions on approaching one another, but not "suffering the least diminution of its force" in the meantime, must be an "outlaw" in the domain of the law of conservation of energy.

The author is not alone in his contention that screening or absorption of gravitational energy is a characteristic of matter. Physicists have returned repeatedly to this idea. Among the many who have conducted recent research along this line is Majorana [Atti dela heale Accademia dei Lincei, v. 28, 1919, v. 29, 1920; Phil. Mag., v. 39, 1920], an Italian physicist who undertook an elaborate series of experiments, using the Eötvös-Schweydar variometer, the Eötvös gravitational multiplicator, and other extremely sensitive instruments, in an endeavor to observe and determine an effect of an absorption of an order of magnitude not less than 10^{-8} of the total intensity of the incident stream of energy. No effect of this kind was then found, and the conclusion was reached that no gravitational screening exists in reality.

This too hasty conclusion would not have been reached by the critics of Majorana, nor, finally, by himself, had the investigators been impartial astrophysicists or geophysicists. A simple calculation shows that should the absorption be of the order of 10^{-8}, the quantity of energy absorbed by the Earth would make it luminous, and that stars subject to this constant absorption would be of the spectral class earlier than B. [The following black-body-radiation formula, based on the exponential formula of gravitation, has been developed by the author of this paper:

$$L = J \times \left(\frac{2Gm}{rc^2}\right)^2 \times \pi^2 r^4 \left[1 - \frac{1}{2r^2\delta^2\beta^2}\left(1 - \frac{1 + 2r\delta\beta}{e^{2r\delta\beta}}\right)\right]^2$$

$$= G \times \left(\frac{2Gm^2}{rc^2}\right) \times m^2 (1 - 3/4\, r\delta\beta + 2/5\, r^2\delta^2\beta^2 - 1/6\, r^3\delta^3\beta^3 + 2/35\, r^4\delta^4\beta^4 - \ldots +)^2$$

δ had not been derived when this formula was developed. L indicates bolometric radiation in ergs, c the velocity of light in cm/sec; other symbols are as used elsewhere in this paper. This black-body-radiation formula shows a satisfactory correspondence between known radius-density and observed bolometric luminosities of stars and planets.]

However, LeSage's theory of gravitation was incomplete and, furthermore, was inconsistent with the third law of motion, as well as with the law of conservation of energy.

In Figure 3, and in the following explanation, the points of inconsistency will be taken up. As was stated by Tait, the Newtonian formula of gravitation can easily be derived from the LeSagian

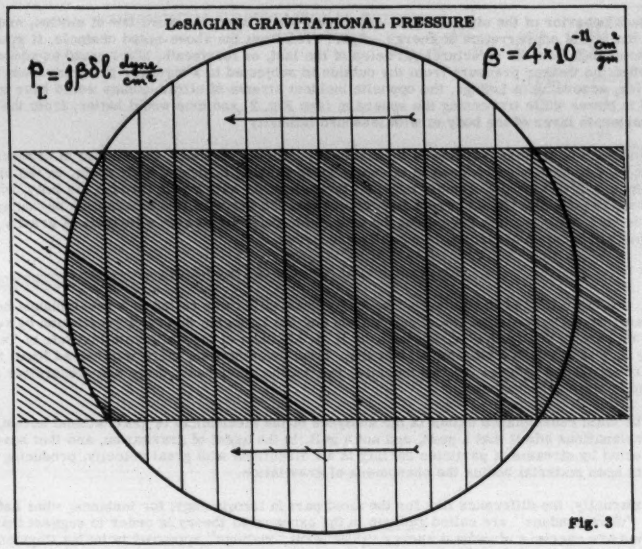


Fig. 3

theory. Therefore, because the Newtonian and the LeSagian formulas of gravitation are mathematically identical, either both of them should be considered correct or both should be labelled incorrect. If it should be proved that one of these two theories is inconsistent, it would follow that the other is inconsistent also, irrespective of however inconceivably small their numerical deviation from the true law of gravitation may be under ordinary circumstances.

In Figure 3 a homogeneous, spherical body m_1 is presented--the same one that is shown in Figure 2. A stream of ultramundane (this is what LeSage called the particles which form his field) is passing through the sphere from right to left. This sphere is divided into 14 layers of equal thickness x and of a density δ, with the planes of the layers normal to the plane of the drawing.

According to LeSage, the pressure exerted upon the cage-structure of a body is proportional to the thickness and the density of the body. In other words, if j be the total intensity (force per gram) of the incident stream, and βj that part of the intensity of the incident stream which produces a pressure p on the structure of one of the layers traversed by the stream (assuming β is 0.05 cm^2/gm in this case), then, according to LeSage, when a pressure p_L is exerted upon all 14 layers of the sphere, $p_L = j\beta\delta\ell$, with ℓ indicating the total length of the path of the stream through the body m_1, that is, ℓ equals 14x in this particular case. The LeSagian theory is then built up in the following manner: $p_L = 0.05\, j\beta\delta x_1 + 0.05\, j\beta\delta x_2 + 0.05\, j\beta\delta x_3 + 0.05\, j\beta\delta x_4 \ldots + 0.05\, j\beta\delta x_{14} = 0.70\, j\beta\delta (x_1 + x_2 + x_3 + x_4 \ldots + x_{14})$, with the subscripts 1 to 14 as the ordinal numbers of the layers.

Now the following question arises: What would happen should the body have, say, not 14, but 25 layers of the given thickness and density? The answer is that the LeSagian gravitational pressure, and correspondingly, the push, would no longer be proportional to the contents of matter in the body. It follows also, according to this analysis of LeSage's idea, that the intensity of the stream of ultramundane acting on the cage-structure of the body remains constant throughout the whole of its path in the body. And this in spite of the pressure produced upon the traversed layers which results ultimately in the locomotion of the sphere m_1 toward the sphere m.

Such behavior of the ultramundane concerned would break the third law of motion, and likewise, the law of conservation of energy. Apart even from the above-noted obstacle, it would be hard to explain how the structural particles of the last, or fourteenth, layer could escape dissipation when the weaker pressure from the outside is subjected to a stronger pressure from the inside, for, according to LeSage, the opposite incident stream of ultramundane would have been reduced in power while traversing the sphere m (see Fig. 2) and thus would batter, from the outside, the fourteenth layer of the body m with lessened intensity.

And here is another instance of inconsistency: On the one hand, the stream of ultramundane is supposed to have been reduced in intensity while passing through a body while, on the other hand, the intensity is assumed to remain constant throughout its entire path through the body, which is obviously impossible. It is of great importance that the error in this assumption be recognized because such a recognition brings out the undeniable fact that Newton's formula of gravity, although seemingly accurate and simple, is actually erroneous.

The exponential formula of gravitation

In the later part of the author's research his attention was called to a resemblance between his theory of the exponential law of gravitation and the LeSagian theory of gravitation by scientists of the University of Cambridge, England, by R. A. Millikan of the California Institute of Technology, and by H. N. Russell of Princeton University. Upon investigation, there was indeed found to be a great resemblance between the two theories, but, on the other hand, there are discernible substantial and decisive differences.

The main resemblance exists in the analyses of the mechanism of gravitational action, for both explanations admit that a push, and not a pull, is the agent of gravitation, and that space is intersected by streams of particles darting in all directions with great velocity, producing by their impacts upon material bodies the phenomena of gravitation.

Externally, the difference lies for the most part in terminology; for instance, what LeSage called "ultramundane" are called radions in the exponential theory in order to suggest that these particles are carriers of radiant energy. [The term "radions" appeared in Indian Physico-Math. J., v. 8, No. 2, September 1937, in paper by Shah Sulaiman, Rotating radions, while in the author's theory the term has been used since 1932.]

Instead of making use of a device like LeSage's cage-structure of material bodies, the exponential theory follows a more modern trend. Material bodies are considered to be built up out of matterons. Just as a brick house is made of bricks, so matter-body is held to be made up of matterons, under which name all structural particles, such as electrons, protons, neutrons, etc., which build up material bodies, are generalized.

The internal difference between the two theories lies, generally speaking, in the degree of accuracy, completeness, and consistency displayed. Fortunately, the research which has given rise to this paper was started when the law of conservation of energy and the kinetic theory of gases had been firmly established. Therefore, in forming this new theory of gravitation, these laws were taken into account, so that the exponential law of gravitation is rendered free from the defects of the LeSage theory and consistent with the third law of motion and also with the law of conservation of energy.

This paper admits that LeSage's concept of gravitation as a phenomenon arising from the effect of the screening of one body by another is, in general, correct, but there are certain deficiencies which must be noted.

In Figure 4 the deficiencies of LeSage's ingenious concept of gravitation are corrected. A stream of radions enters from the right of the sphere, with an intensity j. After j traverses the first layer, that part of j which emerges is $je^{-\beta\delta\cdot x}$. The pressure exerted upon the first layer is $j - je^{-\beta\delta\cdot x}$. For the whole path the gravitational pressure p is shown in the upper-left corner of Figure 4. Upon an expansion of $e^{-\beta\delta\cdot\ell}$ into a series, as is shown in the upper-right corner, pressure p can be represented by the following series:

$$p = \beta\delta\cdot\ell - (1/2)(\beta\delta\cdot\ell)^2 + (1/6)(\beta\delta\cdot\ell)^3 - (1/24)(\beta\delta\cdot\ell)^4 + \ldots - \ldots$$

which becomes practically identical with the LeSagian gravitational pressure p_L, because of the smallness of the coefficient β. Thus the smallness of β is what makes it feasible to neglect the

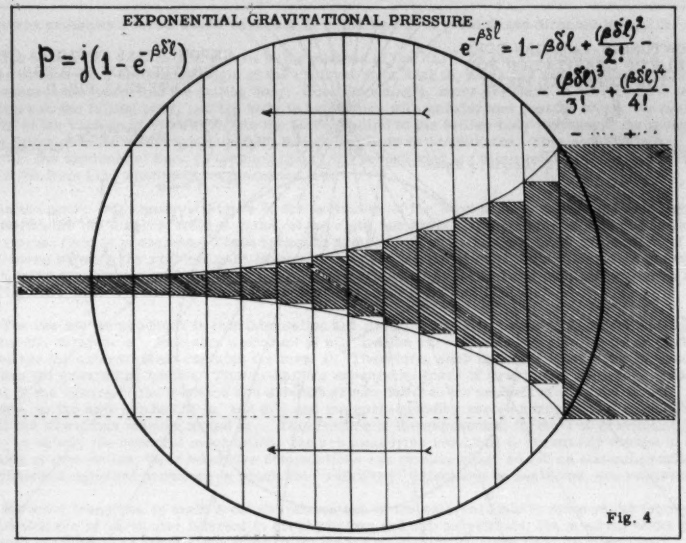

EXPONENTIAL GRAVITATIONAL PRESSURE
$P = j(1 - e^{-\beta\delta\ell})$
$e^{-\beta\delta\ell} = 1 - \beta\delta\ell + \frac{(\beta\delta\ell)^2}{2!} - \frac{(\beta\delta\ell)^3}{3!} + \frac{(\beta\delta\ell)^4}{4!} - \ldots + \ldots$

Fig. 4

higher powers of the series in all terrestrial experiments and causes the Newtonian-LeSagian formula of gravitation to appear sufficiently correct for practical purposes; its discrepancy from the true law of gravitation is due to the omission of the second and higher powers of the series being beyond the reach of the finest scientific instruments.

Finally, it should be noted that the pressure of a radional stream (a stream of radions), while passing through a matteronal structure, drops exponentially, as is shown in the given formulas and in Figure 4. On this account the name "exponential law of gravitation" may be considered an appropriate one for this new law of gravitation.

Before proceeding to a discussion of the LeSagian and the exponential formulas of gravitation, the meaning of density must be elucidated. Density δ is generally accepted in mechanics, physics, astronomy, etc., as gm/cc, that is, mass divided by volume, while δ is quantity of matter divided by volume. At first sight, these definitions may look identical. This impression is incorrect, however, because there is a profound difference between the two.

According to the Newtonian law of gravitation, every cubic centimeter of our globe is considered to weigh, on the average, 5.52 grams. This value is determined by the following method:

(1) f_N is determined as the force by which a body m_1 of known mass at the surface of the Earth is attracted to the center of the Earth.
(2) The radius and volume of the Earth is found by geodetic measurements.
(3) The mass of the Earth is determined from the equation $m = (f_N R^2/Gm_1)$.
(4) The gravitational constant G is determined from direct measurements by the Cavendish method or similar experiments.
(5) $\delta = [m/(4/3)\pi r^3] = 5.52$ gm/cc, with r the radius, m the mass of the Earth, and R the distance from the center of the Earth to the attracted body.

This determination of the mean density of the Earth results from the wrong assumption that every cubic centimeter of the Earth's substance--supposing the Earth to be homogeneous--is subject to the constant intensity of gravitational pressure (see Fig. 3) throughout the entire volume. Actually, as can be seen from Figure 4, the intensity of the gravitational pressure on one cc of

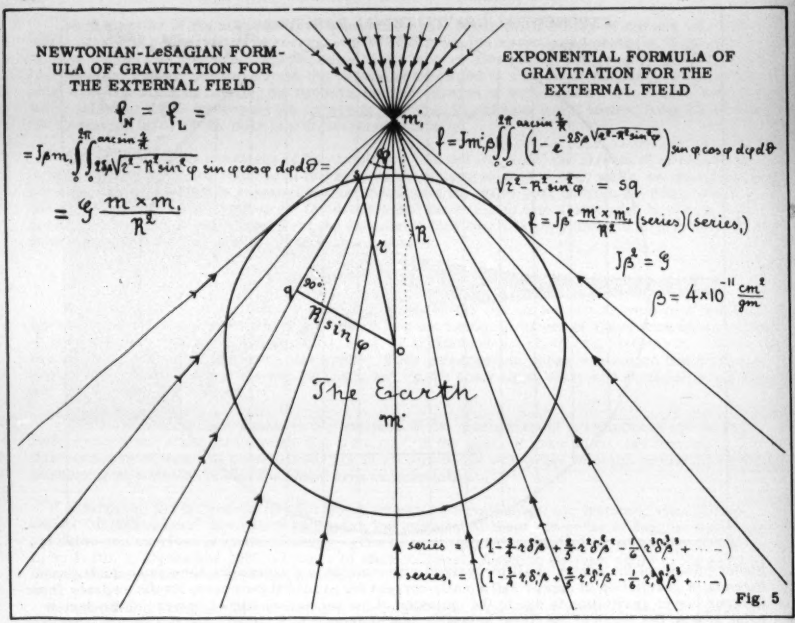


Fig. 5

matter within the Earth will be greater in the layer 9 than in the layers 10, 11, 12, 13, and 14, as well as smaller in 9 than in the preceding layers 1 to 8.

In order to correct this discrepancy, δ' has been introduced into the exponential theory. The unit of this density is the quantity of matter contained in one gram measured at the surface of the Earth. The discrepancy between the quantity of matter in one cc thus determined, and the true quantity of matter in one gram of mass at the surface of the Earth cannot exceed a ratio of $[1/(1 - 10^{-12})]$, by virtue of the magnitude of the constant. [Theoretically speaking, intensity of gravitational pressure on the matteronal structure is not constant even within a single gram of mass.] Therefore, this definition should be considered satisfactory for all measurements at the present stage of science. Consequently the following relationship exists: $\delta = \delta'$ (series), $\delta = [\delta/(\text{series})]$, $m' = [\delta(\text{series})] \times$ volume $= [m/(\text{series})]$; and similarly for δ_1, δ'_1, m_1, m'_2, mutanda mutata. The corresponding series are given in Figure 5.

Figure 5 serves to explain, both from the Newtonian-LeSagian and the exponential point of view, why a body, on being dropped, falls to the ground, that is, to the surface of the Earth.

The circle represents a meridianal section of the Earth. Point m'_1 is a body left in space without any support. The thin arrowed lines represent rays of radions which interconnect m'_1 and the Earth, acting on both of them. The rays on the way to the body m'_1 from below first pass through the Earth and then, reduced in intensity, emerge from the Earth. They then reach the body m'_1 and, in traversing it, produce a gravitational pressure P_1. A like number of radional rays, which fall upon and pass through m'_1 in the direction opposite to that of the rays just mentioned, produce upon the matteronal structure of the body m'_1 an opposite pressure, P_2.

P_2 is greater than P_1 because the intensity of P_2 has not been reduced by passage through the Earth as in the case of P_1. Correspondingly, the sum of these oppositely paired but unequal

pressures produces a force whose resultant is in the line of m_1 and O and directed toward O.

The nearer the body m'_1 is moved to the surface of the Earth by the gravitational force, the larger becomes the enveloping angle of the radional rays, that is, more and more radional rays interconnect the Earth and the falling body. Correspondingly, more pressure is exerted upon the structure of the falling body, and the body is acted upon with greater and greater force, the nearer it falls to the surface of the Earth. As the force applied to the falling body increases, the velocity of the latter also increases continuously, that is, the body is accelerated. This acceleration is called in the exponential theory, acceleration of the second kind, as distinguished from acceleration of the first kind which will be discussed later.

In the upper-left corner of Figure 5, the derivation of the Newtonian-LeSagian formula for gravitation for the external field is given; at the right, the exponential formula of gravitation for the external field is presented. These formulas are derived by an integration of projections of the differences between the radional pair-pressures on the axis, (m'_1 - O). This integration is carried out in polar coordinates with the origin at m_1, through an angle 2π in longitude, and within an angle arcs in (r/R) (one-half the angle of the envelopment of the Earth) in latitude.

The two series produced in this integration are presented at the bottom of Figure 5. In the exponential integral m'_1 indicates a product of m'_1 and the corresponding series. Neither of the series for the external field contains the term R. Therefore, each is independent of the distance between the gravitating bodies. This makes the exponential force of gravitation inversely proportional to the square of the distance and directly proportional to the product of the gravitating masses, so far as a product of m' and m'_1 and the corresponding series corresponds to the product of the Newtonian masses m and m_1. This feature of the exponential formula of gravitation may serve to satisfy the celestial mechanists, who are usually so reluctant to accept any change in the formula of gravitation; their laborious computations can remain intact so far as statical problems or dynamical celestial problems in which the "relativity" effect can be neglected, are concerned.

Before a transition is made from the phenomena of the external field to those of the internal field which are of particular interest to geophysicists and astrophysicists, the meaning of the gravitational constant G as used in the exponential theory of gravitation must first be made clear. An interesting interpretation of the constant of gravitation G is made possible by the exponential theory, as it appears here to be a product of radional pressure times square of the screening-constant β.

In this new definition, the constant G is a product of J, a unit of radional pressure (that is, a unit of force per unit of area, or dynes/cm^2 in the CGS system) and the square of the screening-constant β. From the expression $e^{-\beta\delta\ell}$, it follows that the physical dimension of β is (cm^2/gm) in the CGS system. Consequently, the dimension of G is (dynes/cm^2) (cm^2/gm)^2 = (ML/T^2L^2) (L^4/M^2), that is, the physical dimension of G is $L^3M^{-1}T^{-2}$, in correspondence with the physical dimensions of this constant accepted in physics.

The numerical value for G has recently been redetermined at the National Bureau of Standards by Heyl and Chrzanowski [A new determination of the constant of gravitation, Res. Paper RP1480, 1942, National Bur. Stand.] and found to be $6.673 \pm 0.003 \times 10^{-8}$ cm^{3}gm^{-1} sec^{-2}.

Strictly speaking, G can be considered a constant only on the assumption that J and β are constant. But from the exponential formula of gravitation it follows that neither J nor β is constant in the full meaning of the word, for J is a function of the product $\beta\delta'\ell$ and β is a function of the velocity σ of radional rays.

Thus, in summing up, it may be stated that: (1) G is completely constant in space with no matter; (2) G is approximately constant in the external radional field; (3) G is a variable quantity in the internal radional field.

The idea just expounded may be rather unexpected; nevertheless, it is logical, and the author believes that its correctness can be demonstrated by the predictive ability of the theory in which this idea had its origin.

In Figure 6 the area of the circle represents the interior of a spherical body with its center at O, and a matteron, m_1, at a distance R from the center in the interior of the sphere. Two radional rays of equal intensity fall on the sphere, and after traversing the thicknesses of matter, A and B (see the dotted braces to the right of the rays), and expending therein in passage certain parts of their intensities, impinge upon the matteron m_1 and compress it from opposite sides. [Notice the geometrical lengths of A and B, given in Fig. 6 by the respective algebraic expressions.]

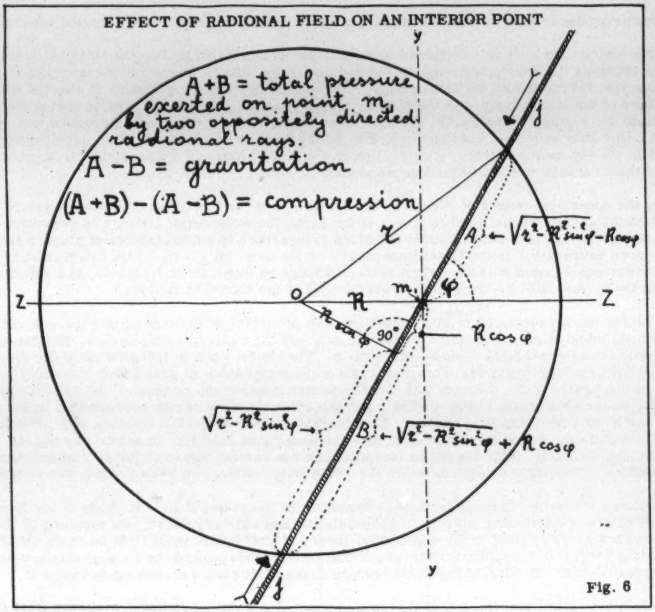


Fig. 6

The pressure produced by the ray passed through A is not equal to the pressure produced by the ray passed through B, because the latter has expended more energy, due to the fact that it must travel a longer distance in its passage through B, than must the opposite ray in its passage through A. The difference between these pressures, called, for brevity, A and B, results in a force which tends to push the matteron m_1 in the direction of the stronger pressure. The projection of this resultant force on the axis Z represents a component of the force of gravity. The sum of the pressures, A and B, on the matteron is the total pressure of the pair of radional rays. The total pressure (A + B), minus the difference (A - B), represents the compression sustained by the matteron m_1, placed at a distance R from the center of the sphere, when the pair of rays makes an angle ϕ with the axis Z. The author believes that this compression is a very important factor in producing earthquakes.

To obtain the exponential formula of gravitation for the internal radional field, a method of integration similar to that employed for the external field may be followed.

The intensity of the pressure of the radional ray j on the matteron m_1 becomes $je^{-\beta\delta' A}$ after crossing a layer of matter of the thickness A and density δ', while the intensity of the pressure of the opposite ray becomes $je^{-\beta\delta' B}$

The difference between these two pressures is $(je^{-\beta\delta' A} - je^{-\beta\delta' B})$. This difference, projected on the axis Z, represents a component of the exponential gravitational force acting on the matteron m_1, in the direction of O. By an integration of this projection in polar coordinates with the point of origin at m_1 through an angle 2π in longitude and from zero to $\pi/2$ in latitude, the exponential formula of gravitation for the internal field is obtained.

The formula at the bottom of Figure 7 is substantially different from the Newtonian-LeSagian formula of gravitation. Aside from the fact that this formula differs from the Newtonian formula

by a more complicated series, this, unlike in the former formula, is not independent of the distance R. The determined functional relation of the parameter $r\delta\beta$ to R leads to the following conclusions:

(1) Exponential gravitational force deviates noticeably from the Newtonian gravitational force within the Earth, stars, and planets.

(2) Lane's law for homologous gaseous spheres does not hold true from the point of view of the exponential theory of gravitation.

In the discussion of the exponential gravitational formula for the internal field, it has been shown that, besides the exponential gravitational force which in Figure 6 is designated symbolically by (A - B), there still remains another force, namely, the force of exponential compression. The role of this new force in the construction and behavior of matter is explained figuratively in Figure 8.

Somewhere in space, a shapeless cloud of matterons has aggregated. Each matteron in space repels every other matteron with a force inversely proportional to the square of the distance be-

EXPONENTIAL FORMULA OF GRAVITATION FOR AN INTERIOR POINT

Exponential pressure is $j(1-e^{-\beta\delta l})$,

Exp. pressure by A ray is $j\left[1-e^{-\beta\delta(\sqrt{r^2-R^2\sin^2\varphi}-R\cos\varphi)}\right]$

Exp. pressure by B ray is $j\left[1-e^{-\beta\delta(\sqrt{r^2-R^2\sin^2\varphi}+R\cos\varphi)}\right]$

$$f = J\beta m^2 \int_0^{2\pi}\int_0^{\pi}\left[e^{-\beta\delta(\sqrt{r^2-R^2\sin^2\varphi}-R\cos\varphi)} - e^{-\beta\delta(\sqrt{r^2-R^2\sin^2\varphi}+R\cos\varphi)}\right]\sin\varphi\cos\varphi\,d\varphi d\vartheta$$

The integral being solved for a homogeneous sphere of radius r and density δ gives the values for the force of gravitation as a function of R, r, and δ

$$f = +J\beta^2 m^2 \cdot \frac{4}{3}\pi R\delta\left[1-\frac{3}{8}r\delta\beta\left(\frac{R^2}{r^2}+1\right)+\frac{3}{16}r\delta\beta\left(1-\frac{R^2}{r^2}\right)\frac{2r^3}{R^3}\ln\frac{1+\frac{R}{r}}{1-\frac{R}{r}}+\right.$$
$$\left.+\frac{1}{10}r^2\delta^2\beta^2\left(5-\frac{R^2}{r^2}\right)-\frac{1}{6}r^3\delta^3\beta^3+\cdots-\right]$$

Fig. 7

tween them, in the same way as electrically and similarly charged particles act. However, the matterons in this cloud (see 1a in Fig. 8) are separated by great distances, so that their repulsive action upon one another becomes negligible.

This cloud is under no external force; therefore, it is equally movable in any direction. It might be pictured as a frictionless, movable car on a rail, equipped with a spring which is under neither stress nor strain (see 1 of Fig. 8), and with an indicator which shows the zero-point on the road.

Shown in 2 of Figure 8 are two lines of bullets (say, from two machine guns) of equal mass and velocity, shooting toward plates at the ends of the spring. Correspondingly, pairs of rays of radions are streaming toward the matteronal cloud from all directions (see 2a).

Depicted in 3 of Figure 8 are the bullets striking on both plates simultaneously, communicating to them their momenta, and making the spring contract. The spring is, in consequence, under a stress of compression which opposes a further contraction as soon as an equilibrium is reached

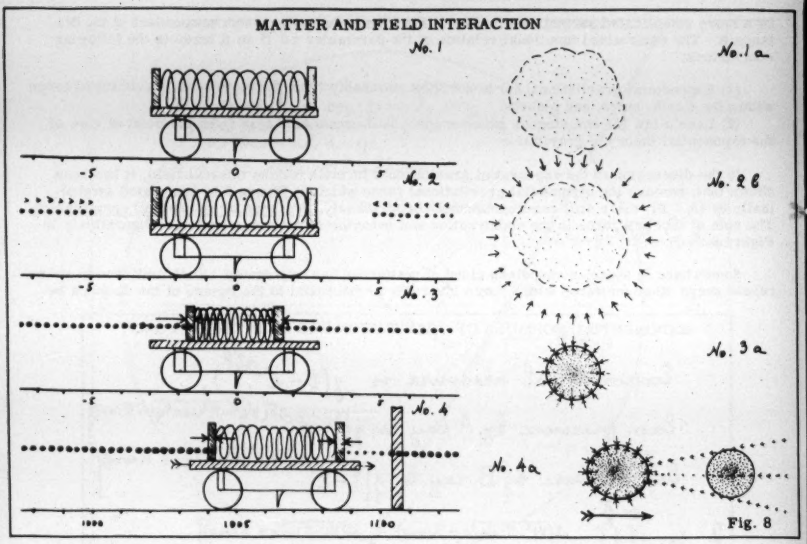


Fig. 8

between the force of the stress and the force produced by the opposing streams (or lines) of bullets. The pressures produced by the continuous impacts of the two oppositely directed lines of bullets are equal; therefore, no locomotive force is exerted on the car by them, and the car's indicator remains at the zero-point.

Correspondingly, 3a of Figure 8 shows the matteronal cloud compressed by the streams of radions into a spherical shape. The repulsive forces among the matterons that are now brought closer together result in a stress inside the sphere which counteracts the radional compression. The internal-stress forces tend to expand the sphere, while, at the same time, the streams of radions from outside tend to compress the cloud back into a smaller size. A delicate state of equilibrium exists under these conditions between the repulsive forces of the matterons and the compressing forces from the radional field--in brief, between matter and field. The equilibrium thus established between the two sets of forces is easily affected by the slightest change in the intensity of the radional field, or by any modification in the shape or density of the body itself. The spherical body thus set into an equilibrium acquires no translational motion in space, though a rotational motion might occur, however, if the distribution of matter in the cloud was not uniform originally.

A screen is shown in 4 of Figure 8, such as a wooden board, set at a distance, say, of 1135 yards from the zero-mark on the road. Bullets coming from the right have to shoot through the screen-board before they strike the plate of the spring. While passing through this board, a certain part of the bullets' momenta is communicated to the board, so that, after traversing the screen and coming out, the stream of bullets impinges upon the spring with a smaller momentum than does the stream of bullets coming from the opposite side (from the left).

Let the initial momentum of each stream of bullets be 100 units, and suppose the momentum intercepted by the screen from the right-hand stream of bullets to be ten units. The pressure on the spring will then be 100 units from the left and (100 - 10) = 90 units from the right. Deducting the weaker pressure from the stronger, a 10-unit difference is obtained. This difference in pressure constitutes a force corresponding to the force of gravitation, which starts pushing the car toward the screen, that is, along with the stronger pressure. With the continuous action of this 10-unit force, the car moves under an acceleration which is called, in the exponential theory, the acceleration of the first kind (compare p. 69).

The acceleration thus produced decreases with the increase in the velocity of the car. As the car moves toward the weaker stream of bullets, the relative velocity of the two streams of bullets with respect to the car varies, namely, it increases for the right-hand bullets and decreases for the left-hand bullets. At the point where the velocities from the two sides become equal and the relative momentum communicated to the spring from each side reaches a value of 95 units, the car acquires a constant velocity, that is, the acceleration becomes zero. The spring is now compressed, from either side, not with a 100-unit pressure from one side and a 90-unit pressure from the other, but with a 95-unit pressure from either side. Consequently, the spring expands to accommodate itself to a new state of equilibrium as compared with the 100-unit pressure on either side when the car was at rest.

It will be noted that 4a of Figure 8 shows a free matteronal sphere being screened by a fixed and rigid matteronal sphere. This screening results in a moving of the free sphere toward the screen-sphere, and in a changing of the shape of the moving sphere into a prolate ellipsoid of revolution (as a first approximation).

Turning back to Figure 5 at this point, every radional ray there depicted may be imagined as a line of bullets similar to one just described. Therefore, the falling body m'_1 may and should be considered as under the effect of two kinds of acceleration, one of the first kind and one of the second.

This symbolical example shows that the expansion of a matteronal body moving through the radional field varies with the different velocities the body displays relative to the field. In other words, a matteronal body's dimensions, and probably its density, are functions of its velocity relative to the field. But it has been shown by the exponential formula of gravitation that the force of gravity is, in turn, a function of the dimensions and densities of gravitating bodies. Herefrom two inferences follow, which, taken together, may be considered as the first prediction to be derived from the exponential theory:

(1) Gravitational interactions of matteronal bodies moving through the radional field must be different from those which occur among bodies which are at rest.
(2) Gravitational interaction varies with the velocities of the bodies involved.

Since our planet must be regarded as a matteronal body, it must be concluded that the rate of expansion varies with the rate of variation in the velocity of the Earth in its orbit. Consequently, with all other conditions equal, disturbances in the Earth's crust should be more frequent during those periods of the year when the velocity of the Earth changes most rapidly. This may be regarded as the second prediction of the exponential theory.

The diagram in Figure 9 answers the question: Why is a material body inside an isolated hollow sphere not attracted by the walls of the sphere, whatever the thickness of the wall may be or wherever the body may be inside the sphere? An explanation of this gravitational phenomenon may be obtained by means of differential analysis of the Newtonian theory of gravitation, but a much simpler solution may be found in the exponential theory of gravitation as shown in Figure 9.

An isolated hollow sphere with a matteronal wall of a uniform thickness ab contains two small bodies, m_1 and m_2. Two oppositely directed beams of equal pressure, j_1, passing through the wall of the sphere, inside upon the body m_1, and similarly, another pair of radional beams, j_2, traverses the wall of the sphere on and in which a certain part of the intensity of each beam is expended, before impinging upon m_2. Because the thickness of the structure of the wall traversed by the oppositely directed beams is perfectly uniform, the quantity of intensity intercepted from the right-hand beam of radions coming to m_2 is equal to that intercepted from the left-hand beam coming to m_2.

Consequently, the pressures on the body m_2 from the left and from the right are equal, and their differences are, of course, zero. Therefore, there is nothing with which to originate a gravitational push, so m_2 is not moved by these pressures. A similar consideration holds true in the case of any other pair of radional beams which may pass through the wall of the sphere and inside upon the body m_2. Naturally the same effect would be produced in the case of m_1 or any other body placed in any position within the hollow sphere with a wall of uniform thickness and uniform density, whatever its thickness and/or density may be.

This illustration shows that the intensity of the radional field within an isolated hollow sphere is different from that outside of it and that the intensity has different numerical values within walls of different thickness or density (or both). The intensity j of the radional field enters the gravitational constant G, wherefrom the following important inference may be drawn: The physical

quantity known as gravitational constant is a variable quantity inside material bodies. Thus it may be seen that one important difference between the exponential formula of gravitation and the Newtonian-LeSagian formula is that the former takes care of the change in the value of the gravitational constant inside of material bodies.

At the bottom of Figure 9 an illustration of one body placed between two others is given. According to the idea just discussed, a similar situation, although of different magnitude, and expressible by a different mathematical approach, exists in the case of a planet placed between two others. It may happen that no acceleration results from the pressure of the two outside planets on the one between them. However, the radional pressure and compression on the middle planet is reduced by the presence of the other two and, like the body inside an isolated hollow sphere, the planet is expanded toward perturbing planets. The diagram at the bottom of Figure 9 represents symbolically a possible alinement of Jupiter, the Earth, and Saturn. Herefrom a third prediction of the exponential theory may be derived: Disturbances in the Earth's crust are apt to occur when the Earth is in line with two or more other planets and between two of them.

In Table 1 the values are given for the Newtonian and exponential forces of gravitation in the interior of a homogeneous spherical body of a radius r equal to 6.37×10^8 cm and a density δ equal to 5.52 gm/cc, corresponding to the mean semi-diameter and the mean density of the Earth. These forces have been computed against R_1 the distance between the center of the sphere, and m, a material point of unity-mass inside the sphere.

In column (2) of Table 1 the distances are given in cm; in column (3) the same distances are expressed in terms of the radius r, while in columns (4), (5), (6), and (7) the first four members of the series are presented according to the exponential formula of gravitation. These have been calculated on the assumption that δ and δ' are identical (see p. 68), according to the following expression:

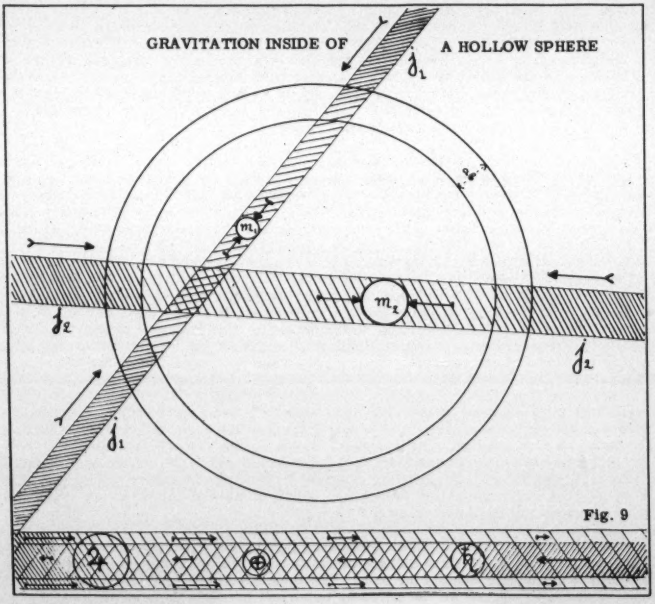


Fig. 9

Table 1--Newtonian and exponential forces of gravitation for a homogeneous sphere of radius $r = 6.37 \times 10^8$ cm and density $\delta = 5.52$ gm/cc, or δ' as explained in the text

No.	R	(R/r)	Members of the series				Sum of the series	f_N	f	f
			1st	2nd	3rd	4th				
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
	km		+	-	+	+		dynes	dynes	dynes
1	6371	1.00	1	0.1054	0.0000	0.0079	0.903	981	885	981
2	5744	0.90	1	0.1176	0.0038	0.0083	0.895	883	790	876
3	5097	0.80	1	0.1352	0.0147	0.0086	0.888	785	697	772
4	4460	0.70	1	0.1604	0.0347	0.0089	0.883	687	604	669
5	3823	0.60	1	0.1993	0.0693	0.0092	0.879	589	518	574
6	3186	0.50	1	0.2637	0.1303	0.0094	0.876	491	430	477
7	2867	0.45	1	0.3132	0.1785	0.0095	0.875	442	387	429
8	2549	0.40	1	0.3823	0.2459	0.0096	0.873	393	343	380
9	2421	0.38	1	0.4180	0.2816	0.0096	0.873	373	323	358
10	2294	0.36	1	0.4597	0.3228	0.0096	0.873	353	306	339
11	2166	0.34	1	0.5090	0.3723	0.0097	0.873	334	270	321
12	2124	1/3	1	0.5274	0.3901	0.0097	0.872	327	284	315
13	2038	0.32	1	0.5680	0.4303	0.0097	0.872	314	274	303
14	1911	0.30	1	0.6387	0.5006	0.0097	0.872	294	256	284
15	1789	0.25	1	0.8966	0.7577	0.0098	0.871	245	213	236
16	1274	0.20	1	1.372	1.232	0.0098	0.871	196	171	189
17	956	0.15	1	2.397	2.257	0.0099	0.870	147	128	142
18	637	0.10	1	5.327	5.187	0.01	0.870	98	85.3	94.5
19	318.5	0.05	1	21.14	21.01	0.01	0.88	49	43.1	47.8
20	106.2	1/60	1	190.0	189.9	0.01	0.9	16.4	14.7	16.3
21	63.7	0.01	1	527.4	527.4	0.01	1.0	9.8	9.81	10.9
22	10.0	$1/(6.37 \times 10^2)$	1	2.14×10^4	2.14×10^4	0.01	1.01	1.54	1.56	1.72
23	1.0	$1/(6.37 \times 10^3)$	1	2.14×10^6	2.14×10^6	0.01	1.01	1.54×10^{-1}	1.56×10^{-1}	1.72×10^{-1}
	m									
24	100	$1/(6.37 \times 10^4)$	1	2.14×10^8	2.14×10^8	0.01	1.01	1.54×10^{-2}	1.56×10^{-2}	1.72×10^{-2}
25	10	$1/(6.37 \times 10^5)$	1	2.14×10^{10}	2.14×10^{10}	0.01	1.01	1.54×10^{-3}	1.56×10^{-3}	1.72×10^{-3}
26	1	$1/(6.37 \times 10^6)$	1	2.14×10^{12}	2.14×10^{12}	0.01	1.01	1.54×10^{-4}	1.56×10^{-4}	1.72×10^{-4}
	cm									
27	10	$1/(6.37 \times 10^7)$	1	2.14×10^{14}	2.14×10^{14}	0.01	1.01	1.54×10^{-5}	1.56×10^{-5}	1.72×10^{-5}
28	1	$1/(6.37 \times 10^8)$		2.14×10^{16}	2.14×10^{16}	0.01	1.01	1.54×10^{-6}	1.56×10^{-6}	1.72×10^{-6}

$$\left\{1 - (3/8)\, r\,\delta\beta\,[(r^2/R^2) + 1] + (3/16)\, r\,\delta\beta\,[1 - (R^2/r^2)]^2\, \ell n\,[1 + (R/r)]/[1 - (R/r)] + (1/10)\, r^2\,\delta^2\beta^2\,[5 - (R^2/r^2)] - \ldots\ldots + \ldots\ldots\right\}$$

Column (8) gives the sum of the series, correct to the third decimal; column (9) contains the values for the exponential force of gravitation, calculated on the assumption that $\delta = \delta'$; and column (10) gives the values for the Newtonian force of gravity within the sphere.

Proceeding on the assumption, already recognized as erroneous, that $\delta = \delta'$, the value for the exponential force of gravitation at the surface of the sphere (R = r) is found to be (903/981) f_N, or 885 dynes, instead of 981 dynes as determined by experiments. Consequently, the values for the exponential gravitational force for all other distances R, within the range from zero to r, are smaller than those of the actual exponential gravitational force by the same ratio of (903/981).

This discrepancy, as has already been indicated, occurs because of the incorrect assumption that $\delta = \delta'$. Therefore, by raising the numerical value of δ from 5.52 until the value given the exponential force of gravity on the surface of the sphere becomes equal to that experimentally determined for it, the true value of δ' is determined. (With f_N equal to 983 dynes, at the surface of the Earth, disregarding the action of centrifugal force, δ' acquires a value of approximately 6.20 gm/cc.) In column (11) the exponential force of gravity is shown as calculated with δ', instead of δ.

To what extent the given values of the exponential force are affected by the non-homogeneity of our Earth is a matter for further investigation. It should be noted that the larger the body, and the higher the value of the parameter, $r\,\delta'\beta$, the greater will be the influence of the given series on the magnitude and distribution of the exponential forces of gravitation within the body. It follows, therefore, that planets larger than the Earth, and, certainly, dense stars and the Sun, will be much more affected than is the Earth by this series.

Constitution of the Earth

The next questions to be discussed are: (1) What happens to the atomic structures subject to the decreased compression (see p. 70) within the Earth? (2) How does the Earth react to this decrease in the radional compression?

Let it be assumed here that electrons whose orbits in an atom (probability of presence according to quantum mechanics) determine the size of the atom, are kept on their orbits by the excess of radional battering against the unprotected sides of the electrons over that on the side protected by the nucleus of the atom (see p. 63), thus applying the LeSagian idea to atomic structure.

If matterons are considered as spheres of the radius a, which is of the order of 10^{-13} to 10^{-12} cm in length, then, with the known mass of electrons, protons, etc., of the order of 10^{-27} to 10^{-24} gram, the densities of the matterons are of the order of 10^{11} gm/cc. This enormous density of matterons causes radional pressure, compression, and exponential gravitational to be exceedingly intense in their action upon the atom, and, besides, the very small value of R between electrons and the atomic nucleus adds to this intensity.

It follows naturally from what has been presented in regard to radional compression (see pp. 70-73) that the nearer to the center of the Earth atoms are, the less they are compressed, the more they are expanded or "swollen." But at the same time the increased gravitational action tends to squeeze them together.

As a result of this interaction of forces, the more the atoms expand, the more they interfere with one another, so that adjoining atoms penetrate one another and ionize, that is, strip one another of valent electrons. In cases where the pressure on the atoms is decreased still more extensively (as in the interior of stars and the Sun), the penetrating process is intensified and then electrons in deeper atomic shells are dislodged.

This picture is somewhat similar to that which G. A. Gamov [The birth and death of the Sun, pp. 160-164, The Viking Press, New York, 1940] gives in his discussion of the collapse of matter. There is a difference in the two treatments, however, for Gamov describes the penetration of atoms into one another as a "collapse" because of excess of pressure due to the weight of the Earth's external layers, while in the exponential theory this process of the "stripping off" of electrons, or ionization of atoms, is depicted as a continuous process, taking place chiefly due to the expansion of the atoms, which increases in intensity with the increase of mass (mass may differ

in different bodies, and, according to the exponential theory, also in the same body when the body's parameter $r\delta\beta$ in the exponential formulas varies) and with the decrease of R, the distance from the expanding atom to the center of the sphere.

Now how do the "swelling" and the resulting ionization of atoms affect the constitution of the Earth? In answering this question, there are two aspects to be considered: (1) The process of ionization in the Earth's interior and (2) the behavior of the Earth as a result of this process.

In the exponential theory, the Earth, unlike the bodies discussed in Gamov's treatise, is considered to be a constant mass acted upon by a constant field, hence, in equilibrium during the process of atomic ionization. Therefore, there is no crushing of the interior by outer layers, but an uninterrupted "step-by-step" expanding of atoms in the Earth's interior due to the effect of a radional pressure which acts upon the Earth's mass with gradually decreasing intensity as its force extends to the center of the Earth. In other words, the degree of "swelling" of the atoms varies progressively with the increasing depth, reaching its maximum at the Earth's center, with the number of free electrons in the Earth's interior varying with the depth in corresponding manner.

Throughout the Earth's interior where atoms are partially disintegrated, free electrons escape and move in all directions. Those of the free electrons that move toward the outside may be captured by less "swollen" atoms nearer the surface, or they may escape entanglement and penetrate to the surface and thence into space.

The free electrons that move inward after liberation dart in among the atoms nearer the center of the Earth, liberating "cascadically" other electrons. Then, with the electrons they have freed that do not escape toward the surface, and with the greatly expanded atoms present, they combine to form a dense core of ionized atoms in electronic gas--"harder and heavier than steel," yet incapable of transmitting transverse seismic vibrations. This property of non-transmission on the part of the hard, heavy, dense core, which may seem paradoxical, is, nevertheless, insisted upon in the exponential theory, and has been found to correspond well with proved observations.

A more thorough study of the suggested process of ionization is needed in order to determine the exact depth of the Earth's layers at which one or another element, or group of elements, starts losing its electrons, through electronic collisions, because of the expansion of atoms. Some possible inferences are now sufficiently clear, however, to be mentioned here, namely: The collision potential of orbital electrons is more than sufficient to serve as an ionization-potential; (2) molecules and atoms with loosely connected valent electrons are the first to be ionized; then, with the further expansion of atoms due to a decrease in radional pressure, ionization among other molecules and atoms follows, the process of disintegration of atoms being in general a function of their ionization-potential and the rate of their expansion.

On the basis of these inferences, as is shown in Figure 10, certain conclusions become plausible, with reference to the constitution of the Earth and the characteristics of its successive layers.

The first layer--This is the Earth's crust, the layer of sial, which is shown in Figure 10 by a heavy line. There is in this layer no noticeable decrease in the radional compression of atomic structures.

The second layer--This is crystallic sima. It lies between the surface and the first broken line in Figure 10. Here expansion of atoms first appears, with the consequent decomposition of pleomolecular systems, beginning at the bottom of the layer, at a depth of approximately 100 km.

The third layer--This is composed of amorphus sima. From the top of this layer to a depth of, perhaps, 400 km the atomic expansion manifests itself by still further break-downs of pleomolecular chemical compounds into monomolecular and monoatomic substances.

The fourth layer--This is also composed of amorphus sima. At the top of this layer, the first ionization of potassium and sodium atoms takes place, giving origin to free electrons which can travel toward the deeper layers or go upward to be captured and recombined with excited atoms which are thus brought back to a normal state. Thus the top of this layer is a boundary which free electrons cannot cross without being liable to imprisonment within an atom. Free electrons remaining beneath this boundary commingle with the atoms and molecules of the layer, increasing the "gas pressure" within the Earth. (It should be remembered that pressure of electronic gas is inversely proportional to the (5/3)-power of the volume occupied.)

CONSTITUTION OF THE EARTH ACCORDING TO THE EXPONENTIAL THEORY OF GRAVITATION

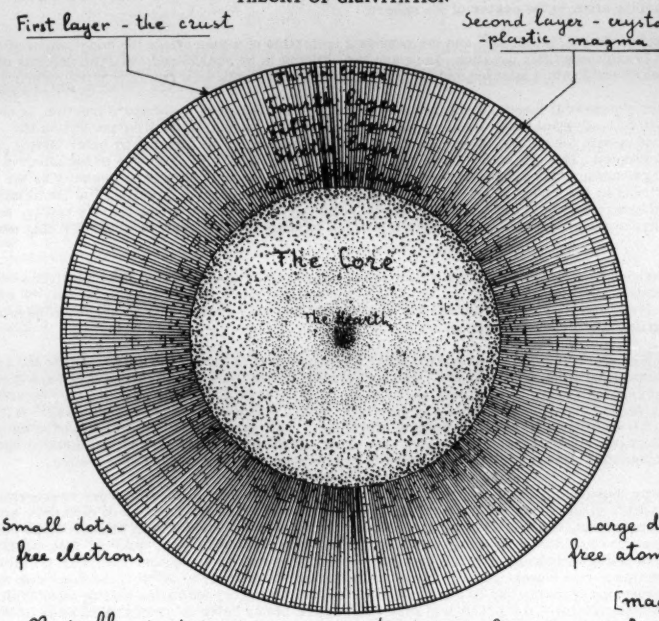


Fig. 10

From the top of the layer to the bottom, a depth of 1200 km, the decrease of radional compression makes atoms expand at a progressively increasing rate, with the consequent ionization of those potassium and sodium atoms which have so far remained in their normal states, and the dissociation of the moelcules in the remaining pleomolecular compounds. Throughout the layer the quantity of free electrons remains fairly constant.

The fifth layer--This is composed of silicates, sulphides, and iron. At the top the aluminum and cadmium atoms start to ionize at a rate exceeding that of the fourth layer and this ionization increases progressively until at a depth of 1500 km, approximately, it reaches its greatest intensity for this layer, with the greatest number of free electrons per cc at this level of the layer. From the depth of 1500 to about 1700 km the ionization proceeds at a progressively decreasing rate. In the whole layer, however, almost all the molecules become dissociated into atoms which are subjected to violent battering from all sides by free electrons.

The sixth layer--This is composed of oxygen, silicon, iron, magnesium, and other elements. The atoms of sulphur and iron start to be ionized at the top of this layer or at a depth of 1700 km. The ionization of the other elements follows at a somewhat lower level, increasing progressively in intensity until the number of free electrons per cc reaches its maximum in this layer at about 2100 km from the Earth's surface. From this level on down to the bottom of the layer at 2400 km,

the rate of ionization decreases progressively, and all molecular structures are completely dissociated.

The seventh layer--This is composed of ionized and normal atoms. Starting from the top of this layer, at 2400 km, and extending to a depth of 3200 km, valent electrons are stripped off all atoms. At the same time, the structure of the layer becomes so "diluted" by free electrons that matter therein begins to "boil", losing some of the solid-liquid phase that prevails in all upper layers. With the increase in depth in this layer, rigidity almost ceases, while the number of electrons per cc continues to grow, increasing the density and elasticity of the layer.

The core--This is composed of ionized atoms in electronic gas. At the surface of the core, or at the bottom of the seventh layer, the rapid decrease in the radional compression of atoms causes several already ionized elements to give up electrons from their second shells or sub-shells. Accordingly, the number of free electrons per cc is enormously increased at this level of the interior. Such a liberal dilution of atomic substance as is thus produced by the free electrons leads to a sudden change in the state of matter in this region from a liquid-solid into a mixture of ionized and excited atoms in electronic gas.

The freed electrons here rush out and concentrate at the center of the Earth, where the content of electrons per cc is at its highest. Atoms are distributed in this inner gaseous sphere according to their "buoyancy"--the lightest atoms "floating" on the surface of a core composed of a gas whose specific gravity is from 8 to 28, approximately.

The hearth--This is the heaviest kind of concentrate of the speediest of free electrons, at the center of the Earth, within a spherical volume of about 100 km in radius.

The preceding analysis gives a simplified picture of the constitution of the Earth, according to the exponential theory. This explanation has sought to provide, briefly, the answer to the first question posed as to how the decrease of radional compression, followed by the expansion of atoms, affects the constitution of the Earth.

In attempting to answer the second question as to how atomic expansion in the interior affects the behavior of the Earth, one should visualize clearly that the structure of the Earth, constituted as has just been explained, is permeated by free electrons from the center of the planet up to the bottom of the third layer, 400 km from the center.

Vehemently darting in all directions, the free electrons tend to expand the whole Earth, that is to say, to burst it. The destructive tendency of the electronic gas is subdued, however, by the exponential gravitational force and by cohesive and viscous properties of the Earth's solid and liquid substance which balance the electronic pressure and establish a state of equilibrium within the Earth.

If our planet were isolated in space and possessed of a constant radional field, such a state of equilibrium could exist eternally. The Earth is not so isolated in space, however, nor is the intensity of its outer radional field absolutely constant. On the contrary, the Earth is under the almost ceaseless influence of other celestial bodies which continually break its internal equilibrium.

In Figure 9 and the explanation following it, the Earth is considered situated between two other planets, expanding, as a result of their screening, into a prolate ellipsoid of revolution, with its major axis in the line of syzygies and with no alteration in the transverse direction. The relaxation of radional pressure permits an increase in the volume of the Earth by providing a chance for the liquid-solid layer around the core to "evaporate" rapidly into electronic gas and add itself to the core, thus causing the core to expand and push outward with a relatively steady, uniform pressure on all sides, and also by allowing the atoms in the other layers to expand and liberate free electrons. These two effects increase the internal expansion and push out the bulges simultaneously, in line of syzygies, in which direction the radional pressure has been relaxed.

When the Earth comes out of syzygies and the cause of its elongation ceases to exist, the planet, because it has to restore its equilibrium, tends to develop into a larger sphere. It should be borne in mind that the electronic gas recently formed in the interior cannot be contracted as easily as could the molecular or atomic gas replaced by it. So, with the resumption of normal radional pressure, the crust of the Earth, composed of solid matter, must, while it is adapting itself to a retraction of the elongation, accommodate itself to a volume equivalent to that of the ellipsoid. When this is accomplished, a new state of equilibrium is established.

Table 2--Positions of planets on date of, and 15 days before and after, the great Indian earthquake of January 15, 1934

Date	Sun	Moon[a]	Planet						
			Mercury	Venus	Mars	Jupiter	Saturn	Uranus	Neptune
			Right ascension						
1934	h m	h m	h m	h m	h m	h m	h m	h m	h m
Jan. 1	18 43	07 20	17 55	21 28	20 22	13 20	21 09	01 28	10 56
15[b]	19 44	19 49	19 32	21 40	21 07	13 25	21 15	01 28	10 55
30	20 47	08 46	21 18	21 19	21 54	13 28	21 22	01 29	10 54
			Declination						
	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′
Jan. 1	-23 05	+24 54	-24 08	-14 38	-20 36	-7 03	-17 26	+8 35	+7 46
15[b]	-21 17	-23 17	-23 39	-10 37	-17 41	-7 28	-16 59	+8 37	+7 51
30	-17 54	+18 59	-17 46	- 8 35	13 53	-7 41	-16 28	+8 43	+7 58
			Log of distance						
	′ ″								
Jan. 1	$\bar{1}$.9927	14 42	0.1426	$\bar{1}$.6089	0.3492	0.7450	1.0283	1.2933	1.4730
15[b]	$\bar{1}$.9929	16 43	0.1555	$\bar{1}$.5125	0.3552	0.7271	1.0327	1.2986	1.4701
30	$\bar{1}$.9935	14 47	0.1285	$\bar{1}$.4393	0.3612	0.7272	1.0353	1.3041	1.4676

[a] Apparent semi-diameter of the Moon is given, instead of its distance from the Earth.
[b] On January 15, the date of the earthquake, note: (a) Moon was at perigee; (b) Mercury at inferior conjunction; (d) Venus not far from inferior conjunction; (e) Jupiter close to opposition.

The Earth experiences a continual repetition of similar or more complicated performances, with configurations of other celestial bodies (the Sun, large comets, and planets), imposing their influences upon it, initiating changes in its shape and increases in its volume, causing stress and strain in the subcrustal layers and in the crust, and contributing to a gradual expansion of the crust which is relatively small, amounting to perhaps not more than a few cm a year, or even less.

This slight expansion is important, however, because it produces important changes in the arrangement of continents and their outlines, for at times, at different locations, when the Earth's skin is stretched almost beyond its elastic limit, only a "hair-trigger" force is needed to break the skin, that is, to produce a fault in the Earth's surface, followed by a seismic vibration--an earthquake. And it is the writer's firm conviction that planetary influences play an important role in this hair-trigger act.

To verify this opinion, there should be a checking of each known earthquake of the past with the planetary configuration at the time of each seismic disturbance--a procedure already worked out by several scientists, but without great success, if not with absolute failure. The radical concept of the constitution of the Earth given in this paper, may, however, let in new light, provide an angle for renewed attack, and supply hope for more successful results in this line of research.

In Table 2 are data on the planetary configuration on the day of the great Indian earthquake in 1934, as well as configurations on the 15 days before and the 15 days after it. This earthquake was picked up at random from N. H. Heck's "Earthquakes", and the tabular data dealing with its occurrence provide some evidence in favor of the suggested planetary influence.

In Figure 11 stage 1 represents a "crack" in the Earth's crust caused by the process described on this page. Two mountains (a and b) are located on the line of the crack, c is a sharp bend in the crack, and a side crack caused by the main crack's splitting around the mountain b is designated by d.

After a crack opens, the Earth's crust immediately below it becomes weaker than at any other point in close proximity. So any continued expansion of the crust tends to widen the crack still farther rather than to produce a stretching and cracking of the Earth's skin at any other point in the vicinity.

State 2 shows a typical result of the widening of a crack in the course of its development. The original crack itself becomes a gulf c′ and, because of the bend in the crack, a peninsula is formed

FORMATION OF SEAS, PENINSULAS, ISLANDS, GULFS, BAYS, ETC., ON THE EXPANDING EARTH ACCORDING TO THE EXPONENTIAL THEORY OF GRAVITATION

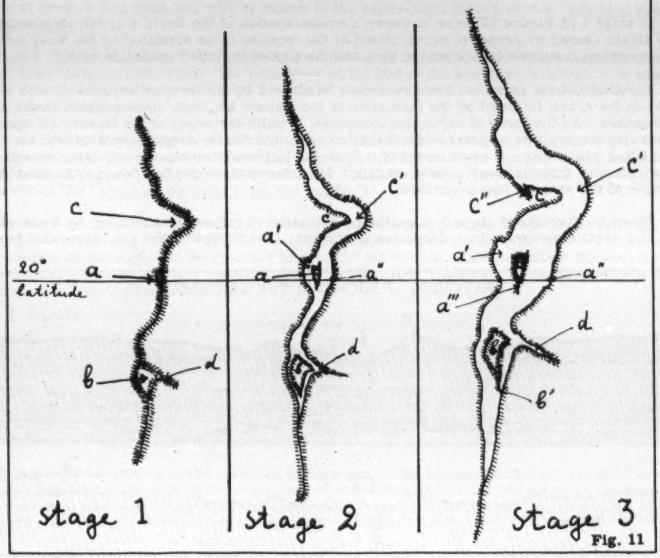


Fig. 11

which projects into the gulf. The islands a′ and b′ are formed out of the original mountains a and b, and the imprints remaining on the shore-line of the straits and the sea after their removal are shown in Figure 11.

It has been found appropriate to introduce the term laceration to describe the process by which the cracks are torn and the gaps are widened in the Earth's crust, and the term nippling to designate the process by which such bodies as peninsulas and islands are elongated. In stage 2 examples of laceration are to be found at c′ and d, and of nippling in peninsula c.

In stage 3 the processes of laceration and nippling extend farther, tearing the already nippled peninsula c off the mainland at the crack c″ and forming, out of the thin extremities of the islands a and b, a chain of islands at a‴ and b′.

The Mediterranean, Baltic, and Irish seas, now lacerated by man in an unprecedented war, provide good examples of the laceration and nippling of the Earth's crust by Nature. Attention is drawn to the following coupled points which give evidence of past laceration and nippling: (1) Sicily and the greatly expanded gulf between Tunisia and Cyrenaica; (2) Crete and the African shore to the south; (3) the Aegean and Marmara seas with intervening breach; (4) the heel of the Italian boot and the Kolpas Bay of Greece (the Peloponnesus Peninsula appears to have been a support to the arch of the Italian boot at the Gulf of Taranto); (5) Ireland and the Anglo-Scotch Island; (6) Plymouth Peninsula, South England, and Grenville Gulf, France (the Plymouth Peninsula is left unnippled because of the adjoining laceration in Bristol Channel); (7) Denmark and the Scandinavian Peninsula, separated by the breaches of Kattegat and Skagerak; (8) the southern tip of Sweden, and the Gulf of Danzig and Kurishes Bay (the shape of the latter is somewhat distorted by sedimentation and erosion).

The above are only a few of the examples that might be cited. A careful analysis of the

coastal lines of seas and oceans throughout the Earth's surface presents undeniable evidence of an expansion of the Earth's surface in all directions rather than a drift or slide in any special direction.

In stage 1 of Figure 12 there is shown a cross-section of the Earth's crust while under expansion strain caused by pressure accumulated at the location b, as indicated by the wavy arrows. The top of one mountain is designated by a and the foot of the other mountain by b.

Elasticity of the crust has been overcome at stage 2 by the force of expansion, with a resulting break in the crust, followed by the formation of the fissure bb', with consequential faults and earthquakes. As the force of expansion continues, it pulls the edges of the fissure bb' apart, thus broadening the gap into a cavity in the Earth's crust, and finally originating what will be a new sea when filled with water. A smaller set of forces due to gravity makes the adjoining massifs of mountains sink into the semi-plastic magma. The formation of the Red Sea may be considered an example of the process just described.

There is, throughout stage 3, a continued extension of the sea by widening, by lengthening, and, in a certain measure, by a deepening of the sea. The bottom of the sea, separated from the

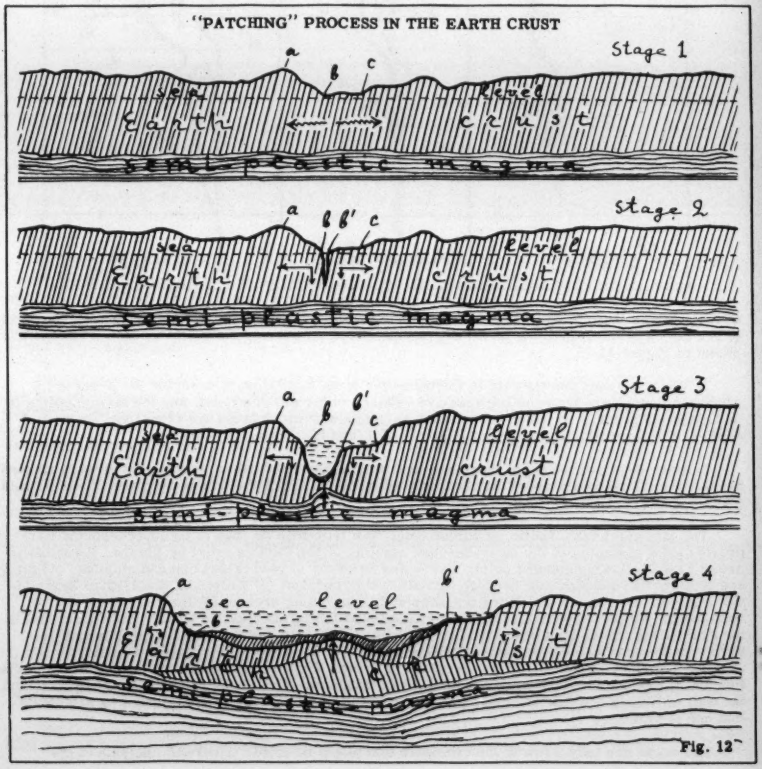


Fig. 12

magma under it only by a comparatively thin layer of Earth substance, yields readily under the hydrostatic pressure of the magma, thus giving origin to "swelling" of central parts of bottoms of oceans and seas. The process of sedimentation which then starts, covering the bed of the sea with deposits of erosion and plankton, will be known in the exponential theory as the "patching process from the outside."

Stage 4 shows the effect of this patching process upon a wide fissure after a considerable lapse of time from its formation. The expansion of the bed of the sea is here shown to be almost equal to that of the crust in general; the sinking of the shore massifs during this stage of the patching process is slight.

As the heat of the magma is conducted to the bottom of the sea and carried out by the water through processes of convection, the cooling magmatic underbed of the sea solidifies, and thus another patch is formed in the Earth's crust. The action here described is known in the exponential theory as the "patching process from the inside."

The patch or bulge of solidified (and therefore lighter) magma (the author found in 1926-27 that molten obsidian and felsite expand on cooling) tends to float, under hydrostatic pressure, on the surface of semi-plastic magma and thus to lift the bottom of the sea above the sea-level, in this manner giving origin to a new continent. The process is stabilized when the bulge's lower level comes to that of the Earth's crust.

The consequences of the Earth's expansion

While the interior expansion of the Earth is going on, the accommodation of the Earth's crust to its enlarged volume, as has been partially explained, is not a process of smooth, easy, even stretching, but a very rough, uneven, and convulsive adaptation, progressing in jerks and jolts. Faults, fissures, breaks, distortions, wrinkles, upheavals, and depressions appear; occasionally, even, a shrinking is caused by the breaking through and bursting out of some of the inner content of the Earth.

This uneven adaptation is the result of unevenness in the intensity and distribution of interior expansion and the unevenness of the resistance encountered. The different areas in the Earth's interior layers, particularly those in the semi-solid layers nearer the surface, are under different and varying strains and stresses, and are also of different degrees of resistance.

At the weaker spots in the subcrustal layers, the accumulated strains and stresses are not caged up for very long, but tend to be released a little at a time through comparatively slight ruptures in the surface, exhibited as fissures, faults, etc.

On the other hand, at stronger spots the reverse takes place. The strains and stresses of expansion may accumulate during an extended period of time without relief. Obviously, any super-strained area, the gradual expansion of which is retarded by pressure and "friction" between and from the immediate upper and lower layers, may eventually rupture in a violent explosion, causing widespread laceration of the upper layers, including the crust, and sometimes bringing about a redistribution of the surfacial masses, thus producing spasmatic changes in the face, the orientation, and the mechanical movements of our planet.

Such an explosion sometimes has, in the past, from all appearances, manifested itself as a cataclysmatic volcanic eruption lifting and throwing into the surrounding space a portion of the crust thousands of square miles in area. At such times the shaken oceans and seas have, without doubt, swept over the lands, destroying the land life. At the time of the larger explosion, minor earthquakes have probably occurred simultaneously all over the Earth's surface, increasing the havoc and devastation.

As many hours would have been required for even the largest rocks--thrown thousands of miles into space--to fall back to the surface of the Earth, and as, in the meantime, the Earth would have been continuing its diurnal rotation, and finally, as the eruption would probably not have occurred exactly in a radial or vertical direction relative to the Earth's surface, the matter hurled forth would doubtless have flown away from the surface at an angle--the disturbed portions would in all probability have been widely distributed over the face of the Earth, seldom landing on the spot from which they were dispersed.

Such a redistribution of internal and external masses probably has resulted in the past and may result in the future in a change in the time of the precession-cycle and a re-orientation of

the polar axis causing, in turn, changes in climatic zones and a redistribution of organic life because of a radical change in the regional climate of the Earth.

A pronounced change in the whole climate of the Earth might also take place at the time following such a super-eruption, for there is a possibility that the tremendous ensuing masses of volcanic dust might envelop the Earth for a long period with a curtain that would probably screen the surface from the Sun and decrease the Earth's insolation.

In the passing of thousands of years under a considerably decreased insolation, a glaciation might follow. Clayton, from statistical studies, and Simpson, from theoretical investigations, have shown that Pleiocene glaciation may have been caused by an increased insolation due to the great quantity of water, evaporated from the surface, which presumably brought about a greater percentage of heat-absorbing vapor in the atmosphere [H. H. Clayton, Solar activity and long-period weather changes, Smithsonian Misc. Collect., v. 78, No. 4, 1926; G. S. Simpson, Mem. R. Met. Soc., v. 3, No. 21, 1928].

These conclusions are based on variations of the solar constant resulting from the eruptions [C. G. Abbot and F. E. Fowle, Volcanoes and climate, Smithsonian Misc. Collect., v. 60, No. 29, 1913; C. G. Abbot, "Arequipa pyrheliometry," Smithsonian Misc. Collect., v. 65, No. 9, 1916] of Krakatoa (1883) and Mount Katamai (1912) and do not necessarily hold for more than a small percentage of variation in insolation.

Beyond a doubt, the presence of substantial amounts of dust between the Earth and the Sun would materially decrease insolation away beyond anything so far observed, although the tendency for this decrease in insolation to lower the mean temperature of the Earth would be offset, to a somewhat negligible degree, by a decrease in atmospheric humidity.

As a result of the loss of a tectonologically appreciable quantity of matter and energy by the Earth's interior during the cataclysmatic outburst just depicted, the interior cools and shrinks, establishing for itself a new state of equilibrium. This contracting of the subcrustal layers causes the Earth's skin to become loosened. In order to regain its former connection with the subcrustal layer, the Earth's crust folds into mountain formations such as may now be observed in the Andes and the Rocky mountains.

The process above described explains the morphologically observed shortening of the Earth's crust during the great epochs of mountain-building, such as the Caledonian, the Hercynian, and others associated with vast continental developments.

As an immediate cause of cataclysmatic eruptions, past or future, which has already been emphasized, the configurations of our planetary system are of prime importance. The constitution of subcrustal layers should be considered as similar to that of tar or of ice. Both these substances are plastic under slow and continuous deformation-forces, but brittle like glass when subjected to instantaneous pressure. Correspondingly, under the enormous strain and stress imposed by the slow process of expansion, the subcrustal layers may yield and adapt themselves without exploding, but with the occurrence of any sudden jolt or jerk produced by the Earth's changing its spherical shape because of planetary influence, these layers would crack. Through openings thus formed, the substance of deeper layers would rush with titanic power toward the outsides, crushing and demolishing everything in its path and making the Earth tremble in cramps and convulsions.

The deeper the layer in which an explosion may be initiated, the greater are the forces there accumulated, but, because, at the same time, the more plastic is the constitution of the layer, it follows that there is needed a sufficiently strong "trigger-force" to act with exceptionally great quickness in order to make possible the instantaneous liberation of energy stored in any of the lower subcrustal layers before the local strain has been relaxed through an adjustment. Consequently, the initiating force of a terrestrial catastrophe is a planetary influence of sufficient power to change quickly the shape of the Earth, rapidly elongating and expanding the globe.

It appears to the writer that the epoch in which a major catastrophe, changing the ebb and flow of the Suess rhythm in morphology, is that in which a configuration of syzygies (formed in the shortest possible length of time) is participated in by all the planets, together with the Earth and the Sun.

Changes in the length of day

There may occur at this point a question as to what part the expansion of the Earth plays in

changing the length of our day. Would not moment of inertia, it may be asked, tend to increase with the lengthening of the Earth's radius, and thus prolong the length of the day, inasmuch as angular momentum must be conserved?

Again, as in answering other questions in this discussion, we must consider two distinct aspects: (1) The effect of a continual expansion of the Earth upon the mean length of the day (this question was proposed to the author by Dr. Archie Blake, Secretary of the Section of Seismology of the American Geophysical Union); (2) the effect of distortions of the globe under the screening effect of other celestial bodies on the variation in the length of the day.

A glance at the formula for the moment of inertia of a homogeneous sphere shows that the calculations necessary in estimating the first effect are not of a complicated nature; indeed, the moment of inertia of a homogeneous sphere at a time t_0 is $m[2/5)\ r^2_0]$, and the corresponding angular momentum is $(2/5)\ mr^2_0\ (\theta/T_0)$, where θ is 360°, corresponding to one complete diurnal revolution of the Earth and T_0 is the period of revolution at the time t_0.

After a lapse of a year, the angular momentum of the expanded Earth would be $(2/5)\ mr^2(\theta/T)$, where T is period of revolution at the time (t_0 + one year), with (θ/T_0) and (θ/T) considered as angular velocities at corresponding moments of time. As the angular momentum has to be conserved, the following equation must be true:

$$(2/5)\ mr^2_0\ (\theta/T_0) = (2/5)\ mr^2\ (\theta/T) = \text{Constant}$$

or, if the mass m of the Earth is considered constant

$$(r^2_0/T_0) = (r^2/T) \quad \text{or} \quad (T/T_0) = (r^2/r^2_0)$$

Let it be supposed that each year the radius of the Earth increases one cm, with a corresponding increase of about 6-1/4 cm in the Earth's superficial expansion. Then

$$(T/T_0) = (6.37 \times 10^8 + 1)^2/(6.37 \times 10^8)^2 \approx 1 + 3.14 \times 10^{-9}$$

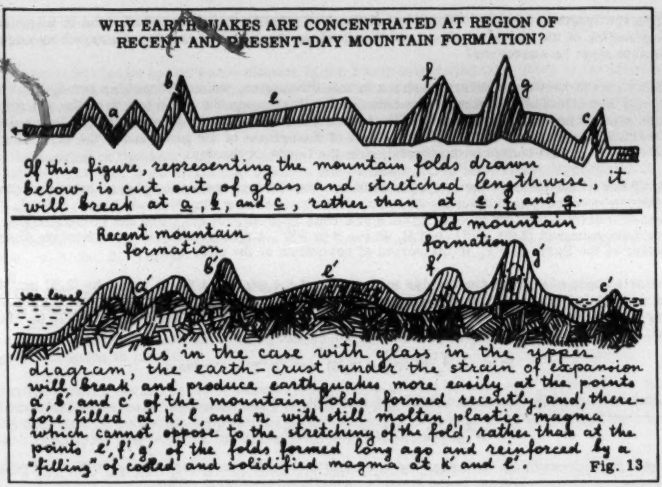
or, to put it in words, the increase in the length of the day, after one year of the Earth's continuous expansion, would be 3.14×10^{-9} of the 24-hour period, or $86{,}400 \times 3.14 \times 10^{-9} = 2.71 \times 10^{-4}$ sec. Thus, assuming the Earth to be homogeneous, this computation shows that expansion of the Earth's surface at the rate of 6-1/4 cm (about 2 inches) per year, would slow down the Earth's diurnal revolution, or would lengthen the day 0.027 sec per century.

But our planet is not homogeneous, nor is its expansion homological. For instance, the Earth's heaviest layer, the one at the surface of the core, is continually "boiling" and dissolving in the electronic-atomic gas of the core, and by adding itself to the core, causes a greater proportion of the matter of the Earth to be distributed nearer its center, thus decreasing the Earth's moment of inertia and, therefore, speeding up the Earth's diurnal revolution. In this way the effect of the Earth's continual expansion on the lengthening of the day is diminished, being less than it appears to be in the above calculation.

Because of this offsetting influence and other compensating factors, an expansion of the Earth as great as 20 inches per year might take place without producing any immediately noticeable effect upon the mean length of the day, although the net effect from the discussed alternate increase and decrease of moment of inertia may be an increase in the length of the day of 0.001 to 0.002 sec per century--as calculated by Fatheringham (1915) from a comparison of the ancient and present-day solar and lunar eclipses.

However, the effect of the Earth's changing distortion of shape and position under the influence of screening by other celestial bodies should manifest itself to a considerably more profound degree. While in syzygies with other planets, the Earth tends to retain the major axis of its ellipsoidal body in the line of syzygies, and there is a consequent slowing down of its diurnal rotation around the polar axis, which becomes more pronounced at times when the major axis of the Earth-ellipsoid is closer to coincidence with the Earth's equatorial plane. In the course of the departure of the screening bodies from the syzygies, an increase in the velocity of the diurnal rotation takes place as the result of the oppositely directed pushes occasioned by the screening effect of these same planets on the extremities of the ellipsoidal Earth.

Consequently, with the coming of the planetary influence, there is a slowing down of diurnal rotation with an increase in the length of the day, and, with its going, a speeding up of the rotation


WHY EARTHQUAKES ARE CONCENTRATED AT REGION OF RECENT AND PRESENT-DAY MOUNTAIN FORMATION?
If this figure, representing the mountain folds drawn below, is cut out of glass and stretched lengthwise, it will break at a, b, and c, rather than at e, f and g.
Recent mountain formation
Old mountain formation
sea level
As in the case with glass in the upper diagram, the earth-crust under the strain of expansion will break and produce earthquakes more easily at the points a', b', and c' of the mountain folds formed recently, and, therefore filled at k, l, and n with still molten plastic magma which cannot oppose to the stretching of the fold, rather than at the points e', f', g' of the folds formed long ago and reinforced by a "filling" of cooled and solidified magma at k' and l'.
Fig. 13

with a decrease in the length of the day. These changes produce a variation in the velocity of the Earth's axial rotation of a cyclical but rather complicated nature, and consequently they produce an alternate lengthening and shortening of the day without affecting the mean value of its length. Such cyclical variation has been observed by E. W. Brown and the observed value, according to the first estimation of the author of this paper, corresponds satisfactorily with the results that would be expected from the exponential theory. It is interesting to note that in his paper [Changes in the length of the day, Smithsonian Misc. Collect., pp. 169-175, 1934] Brown attempts to explain the observed variation in the length of the day by an assumption of an expanding layer of Earth.

Figure 13 provides the answer to the question: Why do earthquakes occur more frequently in the region of recent and present-day mountain development? The Figure is self-explanatory; it remains only to say that the interior and base of the recently formed crust-folds pictured here have not had time enough to cool and solidify the mountain formation into a monolitic block of sial. The interior of recent and present-day folds of the Earth's crust is still molten and plastic, consequently offering little or no opposition to the stretching and breaking of the folded region as the Earth expands.

After a lapse of time, when the mountain formation has grown older, the molten sial in the mountains cools and becomes solid throughout, causing this particular part of the surface to be even stronger than average crust, thus tending to prevent the formation of faults and fissures at this location.

Summary

(1) A new law of gravitation based on exponential interaction between matter and the LeSagian field is proposed and expounded and two new fundamental phenomena--radional pressure of field on matter and radional compression of matter by field--are brought forward and explained.

(2) Two exponential formulas of gravitation are presented as follows:

$$f = G\,(m'm'/R^2)\,[1 - (3/4)\,r\delta'\beta + (2/5)\,r^2(\delta')^2\beta^2 - (1/6)\,r^3(\delta')^3\beta^3 + (2/35)\,r^4(\delta')^4\beta^4 - (1/60)\,r^5(\delta')^5\beta^5 + \ldots. - \ldots.) \qquad (a)$$

for the case of two masses, m' and m', outside of each other; and

$$f = Gm' (4/3)\pi R\delta' \left\{1 - (3/8)\, r\delta'\beta\, [(r^2/R^2) + 1] + (3/16)\, r\delta'\beta\, [1 - (R^2/r^2)^2]\, (r^3/R^3)\right.$$

$$\left. \ln [1 + (R/r)]/[1 - (R/r)] + (1/10)\, r^2 (\delta')^2 \beta^2\, [5 - (R^2/r^2)] - \ldots + \ldots.\right\} \qquad (b)$$

for the case of a small mass m inside of a sphere of radius r and density δ, $\beta = 4 \times 10^{-11}$ cm^2/gm being a new universal constant--the screening-constant--and R the distance between the centers of the two bodies.

(3) The constitution of the Earth as composed of definite layers, the ionization of which increases with their depth, and a gaseous electronic-atomic core of great elasticity and density is suggested, thus explaining non-transmittance of transverse vibrations by the core.

(4) Continuous expansion of the Earth as a whole that goes on between contractions is inferred to be the cause of (a) parallelism in oppositely situated coasts, (b) "swelling" of ocean beds, (c) earthquakes, (d) continuous morphological and tectonological changes in the Earth's crust.

(5) Glacial periods are explained as a consequence of cataclysmic eruptions followed by reorientation of the poles and envelopment of the Earth by a dense "curtain" of dispersed volcanic substance.

(6) Sudden changes in the Earth's surface noted by Suess as accompanying a formation of new continents, oceans, and mountain chains are explained to be the consequence of major contractions which interrupt the continual expansion of the Earth and shrinking of the Earth's crust after a cataclysmic eruption.

(7) The continual increase in the length of the day due to the Earth's net expansion is found to be too small to be observed, unless in a considerable perspective of time, while the cyclical variation in the length of the day, due to planetary influence on the shape of the Earth, is considered to be within the scope of observation.

Conclusion

This study is presented in the hope that it may prove, as have many other purely theoretical discoveries, capable of intensely practical application during this time of war, as well as during the preparations for world reconstruction, serving, by provision of precautionary and salutary measures, in reducing the world's chaos and difficulties.

Consequently, it is the writer's earnest plea that this paper be read patiently, with forbearance for its deficiencies in the working out of details that will take further study to complete and perfect, and with an eye to its possible ultimate contribution to the advancement of science and world progress.

Acknowledgments--It is a great pleasure to acknowledge the helpful and useful cooperation given by suggestion, advice, checking of mathematical formulas, and reading of preliminary manuscripts by the scientists listed below. The names are listed chronologically with respect to the time when contact between the author and the person named was made.

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PROGRESS-REPORT ON SEISMOLOGICAL ACTIVITIES OF THE UNITED STATES COAST AND GEODETIC SURVEY, APRIL 1, 1942, TO MARCH 31, 1943

Frank Neumann

The seismological work of the Coast and Geodetic Survey continued with little interruption during the period covered by this report in spite of some curtailment in personnel and other unfavorable conditions resulting from the war effort. Some major difficulties, however, such as the procurement of recording film, may at any time impose serious restrictions on the current program.

Teleseismic work--In the teleseismic field about 25 stations cooperating with the Survey continued in operation. At one outlying station there was a temporary interruption of about six months, but normal operation was then resumed. The Washington office continues to exchange teleseismic data on important Mexican earthquakes with the Central Seismological Station at Tacubaya and there also has been cooperation with other Latin-American countries in the discussion of earthquake-problems. Special measures have been taken with friendly countries in the Pacific warzone to improve the earthquake-telegram service in order that satisfactory epicenters might be obtained within, as well as outside of, territory of the enemy. In the Washington office 43 preliminary determinations of epicenter cards were issued on the basis of telegraphic data received through Science Service, the Jesuit Seismological Association, and other cooperating agencies. The Survey is extending aid to the Government of New Zealand in the purchase of new seismographs.

In the United States, Benioff three-component seismographs were installed during 1942 at the following stations which are maintained jointly by the Bureau of Reclamation and the Coast and Geodetic Survey: Boulder City, Nevada, March 24; Overton, Nevada, June 6; Pierce Ferry, Arizona, June 30; Shasta Dam, California, July 28; and Grand Coulee Dam, September 12. In the Boulder Dam area this equipment replaces temporary instruments which have been in operation for several years. The new instruments record on 35-mm film (one component to each film) and radio time-signals are recorded on an additional film. Special reading-boards for enlarging the records are necessary to read them. At Shasta and Grand Coulee dams a new, special type of English chronometer is being used. The records are interpreted and reports are prepared by a special seismological party stationed at Boulder City.

At the Tucson (Arizona) Observatory, to insure against interruptions of commercial power the seismograph-recorders have been equipped with 110-volt, 60-cycle, electronic converters and automatic change-over relays so that in case the power fails these devices will cut in and provide emergency service for unlimited periods. The device operates so perfectly that the change-over cannot be detected in the records.

At the Sitka (Alaska) Observatory the Wenner seismographs have been completely overhauled, provided with new coils, special damping-testers, and sealed housings, and have been placed in routine operation in the new seismograph-vault. Also, records are now made on the new Henson recorder driven by a special motor which in turn is controlled by an accurate pendulum-clock. At the South Dakota State School of Mines, Rapid City, a seismograph-vault was provided for in a newly constructed building but no instruments have yet been obtained.

The need for emergency equipment for use in areas where unexpected seismic activity endangers important engineering structures was demonstrated again when a call was sent out for such service from one of our northern Central States. A power-dam was believed to be in danger.

Swarm-activity of the type experienced is not infrequent, and in some cases, as at Helena, Montana, in 1935, may be quite serious. Unfortunately the Survey was not in a position to furnish the requested service.

With the closing of the Philadelphia Computing Office of the Work Projects Administration in September 1942, the task of interpreting the records of about 20 stations was transferred back to the Section of Seismology in Washington. The seismological bulletins through December 1940 have been distributed and the reports through June 1941 are practically completed. Recent progress has been possible through the acquisition of temporary personnel which, though limited in numbers, has proved extremely efficient. An effort is now under way to improve the appearance of the Survey's teleseismic reports which will henceforth bear the title "Seismological Bulletin" instead of "Seismographic Reports".

In the field of special analytical work the Washington office has taken the Tucson record of the Panamanian earthquake of July 18, 1934, and computed the true displacement for both horizontal components, using all three terms of the equation of motion which involves a single and a double integral. An outstanding feature of the work was unquestionable evidence of the existence in the S-wave group of a slow "tilting" effect lasting about 30 seconds. On the original record it corresponds to a perceptible temporary shift of the zero-position of the pendulum. On the first integral it appears as a sudden downward slope of the axis of the curve followed by a return to normal. In the January 1942 number of the Bulletin of the Seismological Society of America, C. F Richter calls attention to a similar motion on the Wood-Anderson records of the nearby Whittier (California) earthquake of January 29, 1941. The investigation shows that this phenomenon is not limited to the records of nearby earthquakes, as the epicentral distance in the case of the Tucson record is over 3900 km.

Earthquake-information service--The program for the collection of earthquake information continued as heretofore. In the Pacific Coast and Western Mountain States several thousand new cooperators were added to the approximately 40,000 cooperators reporting to the Bureau's Seismological Field Survey headquarters in San Francisco. There has been no change in the personnel of State collaborators as listed in last year's progress-report. These men are performing excellent service and at no cost to the Government.

The quarterly "Abstracts of earthquake reports", which contains all of the material collected in the far West, has been modified to the extent of excluding certain information not considered essential to a satisfactory description of earthquake-effects. As in the case of the Seismological Bulletins, steps are also under way to improve the appearance of the Abstracts.

No earthquakes of outstanding importance were reported from the Pacific Coast and Western Mountain States in the past year. A moderate shock in New England on January 14, 1943, was canvassed by the Weston College Seismological Station, cooperating with the Coast and Geodetic Survey; and the Washington office canvassed the Lake Erie earthquake of March 8, 1943. Both shocks were of rather moderate intensity. Weather Bureau observers furnished valuable reports on these and other shocks as a part of their cooperative program of preparing monthly reports on seismic activity.

It is gratifying to report that the Bureau of the Budget has excepted the earthquake-information forms of the Survey from the ban placed on many other Federal questionnaires.

Strong-motion work--The 53 strong-motion stations of the Survey and cooperating agencies continued in operation with only a few changes. An accelerograph was transferred from Golden Gate Park to the University of San Francisco, and preparations are being made to transfer the one at Missoula, Montana, to Great Falls. Due to a reduction in the personnel of the Seismological Field-Survey party, the servicing of instruments in the field has been cut down to what is considered an irreducible minimum, and all work on instrumental development has been postponed. During the year 30 strong-motion records were obtained from five shocks, all of only moderate intensity.

When the Survey accelerometers were originally designed, one of the unknown factors was the maximum acceleration to expect in destructive earthquakes. After less than ten years' experience it is clearly evident that most of these instruments, while having satisfactory sensitivity, do not have sufficient recording-range. This applies to both accelerographs and displacement-meters. A study of accelerograph-records in southern California revealed that the older type of accelerograph, with six-inch drum, would be satisfactory for recording a major shock only if the instrument were on rock.

Ground-factors, as determined from all the maximum accelerations recorded to date, were found to agree to a surprising degree with the factors developed by H. O. Wood in his investigation of the earthquake of 1906. As a result the sensitivities of the accelerographs in southern California were changed to conform to the following schedule of recording capacities: 0.25 gravity on rock; 0.40 gravity on conglomerates; 0.70 gravity on river alluvium; and 1.0 to 2.0 gravity on the top floors of tall buildings. In accomplishing this it was found necessary to reduce the sensitivities of some groups of instruments by reducing the pendulum-period from 0.1 to 0.07 sec. In the San Francisco Bay area there have not been sufficient data to carry through an analysis similar to that for southern California.

The final report on the accelerometer shaking-table tests conducted at the Massachusetts Institute of Technology in 1936 was published by Messrs. Ruge, McComb, and Neumann in the January 1943 number of the Bulletin of the Seismological Society of America in the form of a symposium.

The quarterly progress-reports on strong-motion work were issued on schedule.

In the Washington office the displacement was computed (by integration-methods) from the following acceleration-records: Hollywood Storage Company building, top and bottom, October 2, 1933; Vernon, March 10 and October 2, 1933; and Ferndale, September 11, 1938. The computed curves will be published in the forthcoming annual seismological report of the Bureau for 1941, but it is being found necessary to postpone the period analysis of the computed curves. This is expected to give results somewhat similar to those obtained in the analysis of the El Centro record of the Imperial Valley earthquake of May 18, 1940.

Vibration-work--On the west coast 14 vibration-observations were made in seven buildings, four were made in connection with blasting operations, and two series of heavy machine-vibrations were made. Part of this work was done in connection with defense projects in which the effect of vibrations on nearby precision machines was investigated. In the east, vibration-instruments were loaned to the Woods Hole Oceanographic Institution, while others were loaned for a study of the vibrations of the Potomac River (Morgantown) Bridge.

General--The Ground-Water Division of the United States Geological Survey and the Coast and Geodetic Survey have inaugurated a cooperative program whereby the Coast and Geodetic Survey will furnish all ground-water stations immediate epicenters, and the Geological Survey will furnish the Coast and Geodetic Survey the results of water-level fluctuation in deep wells due to earthquakes. The latter data will appear in the Survey's annual seismological records.

In connection with the effort to reduce the size of mailing lists for Government publications, the following seismological reports of the Survey were exempted by the Office of War Information from its rigid requirements governing the canvassing of mailing lists because of the cooperative character of seismological work and the fact that, through this cooperation, the Government received information which could not otherwise be obtained except at great cost: Seismological bulletins, Abstracts of earthquake reports for the Pacific Coast and Western Mountain Region, and Progress-reports on strong-motion work.

Included among Government projects aiming at closer cooperation with South American countries in the field of science is a project involving the occupation of many magnetic stations and visits to seismological stations by a field-party of the Coast and Geodetic Survey. The party, consisting of Joel B. Campbell and Fred Keller, Jr., is still in South America. Seismologists of the United States will be interested in the following information regarding seismological activities among our southern neighbors.

At the Astronomical Observatory in Quito, Ecuador, excellent records are being obtained from two Mainka smoked-paper recorders, but the time-control is inadequate according to present-day standards; three other seismographs are held in reserve. In Guayaquil the party found plenty of evidence of the strong earthquake of May 14, 1942, which damaged many buildings in the city.

At Caracas, Venezuela, an inverted Wiechert pendulum is operated at the National Observatory. The Geological Survey of Venezuela is interested in having a more active seismological program adopted by the Government.

In Bogota, Colombia, the seismological station of the Jesuit School at San Bartolomé is directed by Father Ramirez who is well known to many American seismologists. A description of the station and the new equipment recently installed will appear in an early issue of the Bulletin of the Seismological Society of America. Operation of the new Benioff seismograph was temporarily sus-

pended during the winter because of difficulty in obtaining photographic paper, but it is now operating again.

At the Jesuit San Calixto Observatory near La Paz, Bolivia, the party found the normal routine of the station curtailed by lack of photographic paper. This station normally operates three smoked-paper instruments and three photographic recorders, but of the photographic recorders only one vertical component was being operated. This station also operates a subsidiary installation at Sucre, about 250 miles southeast of La Paz.

At Lima, Peru, a Wiechert seismograph is operated by the local seismological service, but no time-marks were being recorded at the time of the visit, and operation was evidently intermittent. Some sentiment was found among local officials for an improved seismological service.

At Santiago, Chile, the station of the Seismological Institute sponsored by the Government of Chile was in process of being equipped with several new types of instruments by its Director, Dr. Federico Greve, an engineering professor of the University of Chile. There will shortly be in operation nine components of four different types of seismographs, evidently all recording on smoked paper, and a newly built Ishimoto accelerometer. A Wiechert horizontal combination is now operating at Copiapo, and six Bosch-Omoris of the type in operation in Santiago are being built for installation at Copiapo, Concepcion, and Puerto Montt. Additional accelerometers are being built for subsidiary stations. Dr. Greve has also inaugurated a rather extensive earthquake-information program.

Another station in Santiago is that of Dr. Julio Bustos Navarette. This is a private observatory containing magnetic, seismological, and other equipment, much of it of experimental character.

U. S. Coast and Geodetic Survey,
Washington, D. C.

THE SEISMOLOGICAL INSTALLATION AT THE SITKA MAGNETIC OBSERVATORY

R. E. Gebhardt and J. H. Nelson

(Approved by the Director, United States Coast and Geodetic Survey)

Due to the various defense projects started at Sitka during 1938 and 1939 and the resulting influx of construction workers, there was brought about an acute housing shortage in the town. In order to meet the demand for houses and apartments, a large number of small dwellings were hastily constructed. A number of these new buildings were erected very close to the buildings of the Observatory and the continuity of the magnetic observations at the Sitka Observatory was threatened. Land belonging to the Department of Agriculture and used for an experimental farm was transferred to the Coast and Geodetic Survey as a site for the Observatory. A special appropriation from Congress made it possible to construct new buildings at this site, and the Observatory was moved to this location on the outskirts of the town of Sitka in the fall of 1940 [see 1 of "References" at end of paper].

Only one structure on the old experimental farm was of a permanent nature and capable of rehabilitation. This structure was originally used as a root-cellar and was of reenforced-concrete construction built into the side of a hill. The back wall was of 14-inch reenforced concrete entirely below the normal ground-level. The two sides were partially exposed and the front was entirely exposed. To maintain uniform temperatures for the storage of bulbs and plants, etc., the exposed walls were made double and each of the walls separated by a three-foot air-space. A reenforced-concrete roof covered the inner section. The original root-cellar had a wood gable-roof, but at the time the Coast and Geodetic Survey acquired the property the wood section was badly rotted and needed replacement. The vault had a concrete roof or ceiling and this concrete was waterproofed with several applications of asphalt and a three- to four-foot earth-fill placed over the entire structure. It was necessary to extend two ceiling ventilators through the fill in order to provide ventilation of the vault.

Several years ago J. H. Nelson of the Coast and Geodetic Survey saw the description of a device for driving an astronomical telescope with an induction-motor. It had an electrical circuit so arranged that the speed was controlled by a short impulse once per second from the sidereal clock. The impulse from the clock turned on the power for the motor and a cam on the motor-shaft interrupted the circuit after about one-half second. The speed of the motor during the first part of

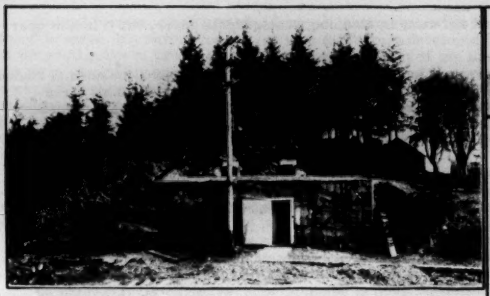


Fig. 1--Seismograph-vault, Sitka Magnetic Observatory (just before completion of wiring and installation of seismograph)

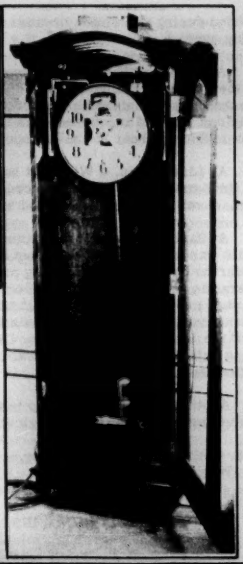
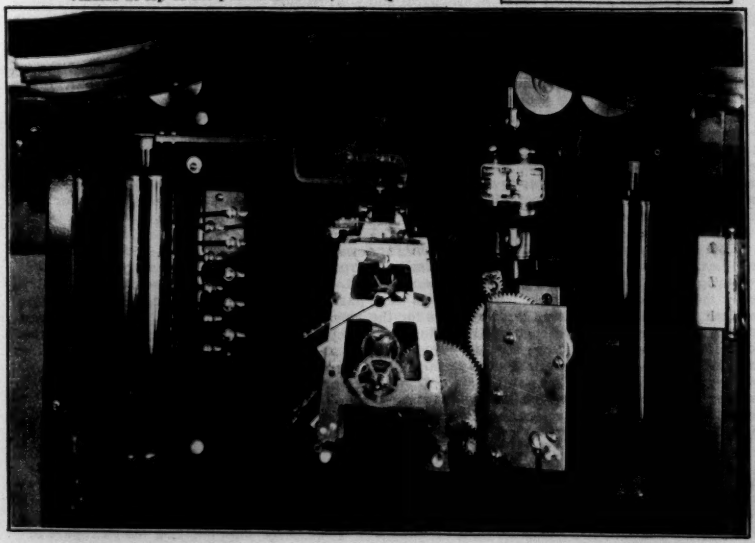


Fig. 2--Observatory pendulum-clock

Fig. 3--Close-up of clock-movement (seconds-contact visible at top of the pendulum-staff)



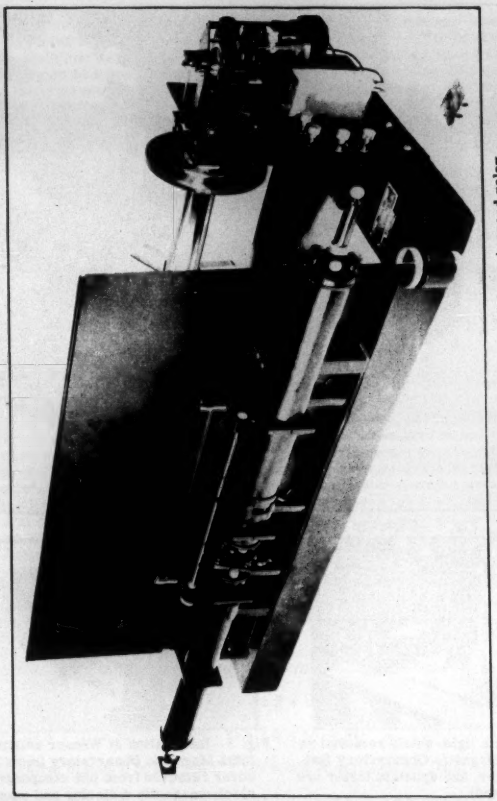


Fig. 4--Seismograph recorder showing lamp-housing, motor, and relay for locking electrically circuit to motor

the second was too fast, and after the power was turned off was slower than the desired speed. Once the motor was running normally, and if the speed during the first part of the second was too great, the cam would operate sooner, thereby shutting off the power for a somewhat greater interval.

This principle was used on one recorder built by the Survey and was found to be very satisfactory, but the motor used on this first model required a fairly large current for its operation [2]. Later a small motor-device used for flasher-mechanisms was used on the recorder. The current required for its operation is very small and the motor can be operated for about a year on three or four dry-cells. The second-impulses are supplied by the pendulum-clock and the speed-control is very uniform. The recorder equipped with this motor was operated for only a short time in the Washington office before it was sent to Sitka and placed in operation in April of 1940. The drum-speed is controlled through the Observatory pendulum-clock and is very uniform.

The Observatory pendulum-clock was replaced in 1940 with a clock having an invar staff and metal bob. The clock is equipped with contacts that operate once per second, once per minute,

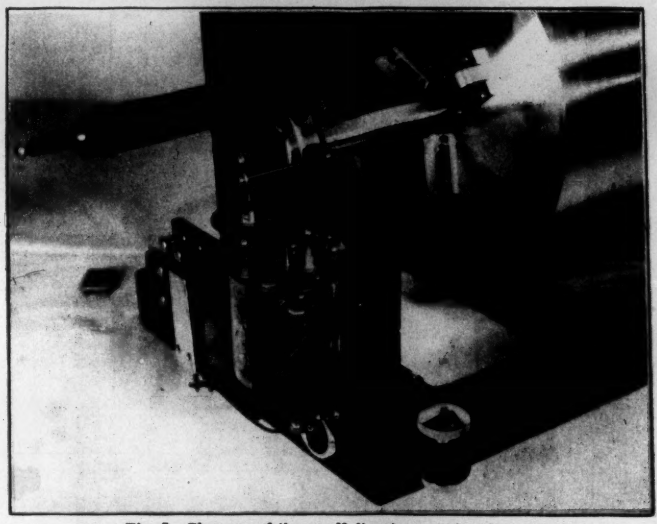


Fig. 5--Close-up of the small direct-current motor

Fig. 6--Recorder with light-shield removed as operated at Sitka Magnetic Observatory (galvanometers, bridges, and dynamic tester are visible in foreground)

Fig. 7--Installation of Wenner seismometers at Sitka Magnetic Observatory (metal air-tight cover removed from one component, showing electromagnetic deflector and small beaker of calcium chloride)

and two separate sets operate once per hour. The rate of the clock is about one-tenth second per day. It is compared daily with signals from one of the Naval radio stations.

Upon moving to the new site the Wenner seismometers operated at Sitka since December 1932 were removed and returned to the Washington office of the Coast and Geodetic Survey for cleaning and overhauling. The instruments were equipped with an electromagnetic device for deflecting the seismometer-boom for damping-tests, with new non-magnetic coils of a slightly smaller size in order to increase the clearance in the air-gap of the pole-pieces. Special air-tight metal covers were also installed at this time so that the air in the instrument-chamber could be kept dry and excessive corrosion of the metal parts prevented. The installation of the electromagnetic damping-device brought up an interesting problem in stresses in castings and base-plates. Previously the instruments from the San Juan Observatory had been overhauled and equipped with an electromagnet that was placed on the pier under the corner of the base-plate. The magnet, when energized, pulled the corner of the base-plate downward and the tilt introduced caused a deflection of the boom for damping-tests, etc. When this system was installed on the Sitka instru-

ments, it was found that the one component responded in the desired manner; however, the second component was deflected in the opposite direction from that expected. The trouble was finally located in the base-plate and was apparently due to strains in the casting. It was then necessary to move the electromagnet to a position on the vertical frame and place a small piece of soft iron on the boom. This material was placed well away from the large permanent magnets of the seismometer. This device is very satisfactory and very positive in its action. The instruments were returned to Sitka in 1942 and installed in conjunction with the motor-driven recorder just described.

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RECENT RESULTS OF EARTHQUAKE STUDY IN SOUTHERN CALIFORNIA

B. Gutenberg and C. F. Richter

(Abstract: Contribution No. 356, Balch Graduate School of the Geological Sciences)

This report covers results which are partly already published, partly in course of publication, and partly still in preparation. The first synthetic study of earthquakes in southern California was published in 1932 [see 1 of "References" at end of paper]. In recent years available data have been much improved, owing to the installation of Benioff seismometers with high magnification at most of the stations, the establishment of new stations, and better chronometer-timing (six time-signals from the Naval Observatory are automatically recorded each day). Much experience in the interpretation of local seismograms has been gained with the continued occurrence of more and larger local shocks. The labor of calculation has been reduced by preparing special tables which quickly yield distances to 0.1 km [2].

Fifty of the larger and better recorded shocks (all but five later than 1937) have been selected for study. Epicenters, origin-times, and preliminary results for travel-times and structures have been published [3]. The mechanism of faulting, as inferred from the direction of first recorded motion, agrees with the result of previous work [4].

Typical travel-times for the region, revised to date [5], are as follows:

$\overline{P} - O = D/5.577$ $\quad Py - O = 1.2 + (\Delta/6.05)$ $\quad Pn - O = 6 + (\Delta/8.06)$

$\overline{S} - O = -0.5 + (D/3.26)$ $\quad Sy - O = 2.0 + (\Delta/3.64)$ $\quad Sn - O = 8 + (\Delta/4.46)$

where Δ = epicentral distance in km and D = hypocentral distance for focal depth 18 km.

The terms independent of Δ in the equations for Pn and Sn show appreciable variation for shocks in different parts of the region, with maxima of about 9 and 13, respectively, in the shocks of northern Owens Valley east of the Sierra Nevada. This is an effect of the "root" of the Sierra, which has been discussed in connection with mountain roots in general [6].

The travel-times indicate no variation in the thickness of the "granitic" layer, which is about 18 km. Most of the shocks originate near the base of this layer. There is at least one intermediate layer between this and the base of the continental crust (the Mohorovičić discontinuity). The velocity of Py in this layer differs notably from that of the similar wave P* as observed in Europe (6.05 instead of 6.4 km/sec). If this is a single layer, its thickness varies from about 20 km in the coastal area to almost 50 km in the Sierra region.

The term -0.5 in the equation for $\overline{S}$ represents a frequently noticed discrepancy between the apparent origin-times of $\overline{P}$ and $\overline{S}$. The writers attribute this to development of the fault-fracture with speed greater than the velocity of transverse elastic waves, resulting on the average in early arrival of S at the observing stations. An exact theoretical discussion is in course of publication [7].

Measurement of recorded amplitudes for the 50 shocks afforded an opportunity to refine and revise the magnitude-scale for local earthquakes [3]. No significant corrections to the standard amplitude-distance curve were required except at short distances. Using additional data from strong-motion instruments at Pasadena and at the stations operated by the United States Coast and Geodetic Survey, the relation of the instrumentally determined magnitude and of the macroseismic intensity to energy-release and to acceleration has been discussed [8]. The method of the magnitude-scale has been applied to determine the variation of amplitude of the principal P- and S-phases individually, which gives information as to the variation of velocity with depth [9].

The following are mean values of elastic constants (cgs) from all available data for the region:

Layer	Bulk-modulus	Rigidity	Poisson's ratio
Granitic	4.5×10^{11}	2.9×10^{11}	0.24
Intermediate	5.5×10^{11}	3.8×10^{11}	0.22
Below intermediate	12.4×10^{11}	6.5×10^{11}	0.28

A new application of the magnitude-scale is in course of development by J. M. Nordquist. In constructing statistics of occurrence of earthquakes, even with the assistance of the magnitude-scale, there has hitherto been difficulty in making appropriate use of data for both larger and smaller shocks, since the larger shocks represent almost the entire release of energy in the period during which they occur. Further, the statistics are imperfect both for the largest shocks, on account of their infrequent occurrence, and for the smallest shocks, on account of incomplete registration and imperfect location. The new method provides a means of correlating the occurrence of large shocks with that of small shocks, and takes account automatically of the imperfect representation at the two ends of the scale. The procedure is to divide the period investigated into equal time-intervals, and to count the number of these intervals in which the largest shock is of a given magnitude (magnitudes being ordinarily assigned to the nearest half-unit). Assuming a special distribution-function already employed in the investigation of flood-statistics [10] makes it possible to choose a scale for a plot in which the points for various magnitudes fall nearly on a straight line, the level of which is an indication of the degree of activity. The method promises a quantitative definition of seismicity.

A recent large shock, not included in the studies referred to, occurred in the region of Borego Valley, San Diego County, on October 21, 1942. This was well recorded at all the regular stations in and near southern California, and numerous aftershocks were recorded with a portable instrument at temporary locations. Preliminary epicenter and origin-time for the main shock are: 32° 58′ north, 116° 00′ west; O = $16^h\ 22^m\ 14^s$, October 21, GCT. The magnitude was about 6.5. A large following shock had a very different epicenter: 33° 18′ north, 115° 41′ west; O = $01^h\ 50^m\ 38^s$, October 22, GCT; magnitude 5.8.

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TWENTY-FOURTH ANNUAL MEETING

SECTION OF METEOROLOGY

REPORTS AND PAPERS

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DETERMINATION OF ICING-CONDITIONS FOR AIRPLANES

David L. Arenberg

The physical conditions necessary for the icing of aircraft have long been observed and understood by meteorologists but only when aviation became an important factor in present-day transport did the processes receive more than the passing attention of a few specialists. At present, icing compares with fog and turbulence as the chief hazard to flight.

It is proposed in the following discussion to analyze the various meteorological factors involved with a view towards enabling better forecasts of icing-conditions to be made. Due to the complexity of the phenomena, little attempt at a theoretical treatment can be made.

The term icing as applied to aircraft covers the deposit of ice in three forms. The first is frost or hoar and is seldom of importance. The two others, rime and clear ice, occur when liquid water is deposited by an air-stream and frozen. Both are amorphous and the distinction lies in the lower density and open, rough structure of the rime because of the large proportion of enclosed air. The density of rime increases with temperature and rate of deposit as affected by wind-velocity and liquid water-content.

Clear ice is usually formed at higher temperatures and, it is thought, with larger drops than rime. The term glaze, which is at present confined to ice formed from freezing rain outside of a cloud, might better be adopted for this formation. Even the densest ice is seldom clear but usually opaque and milky, while the word ice itself is applied rather loosely to all three forms in the literature. The border between rime and glaze occurs at a density of 0.75 and 0.80 gm/cc and there are important differences in strength, adhesion, roughness, and rate of growth under otherwise similar conditions.

The rate of deposit will depend on the product of the liquid water, relative velocity of plane, and collector-efficiency. The latter term may be defined as the ratio of the water retained (not simply impinging) to that contained in a prism having the length of the motion between air and object as its altitude and the projected area in the direction of flow as its base. The rate-of-growth or accretion measures the length of the deposit; hence it is inversely proportional to the density.

Even for simple shapes the collector-efficiency cannot be evaluated but it can be shown by dimensional analysis that

$$\lambda = C\, F\,[(VD)^m/\mu\,]\, f\,(D/d)^n \qquad (1)$$

where C is a constant, V is relative air-velocity, D is diameter of drop, d is diameter of collector or representative dimension, μ is kinematic viscosity of air, m and n are positive exponents, and F and f are suitable functions.

For large cylinders and drops obeying Stokes' law, m and n are both 1 and the functions are linear while C is 0.1111. Spheres and flat plates have been used as collectors but there is little possibility of correlating the few quantitative measurements with each other. While cylinders are preferable, the collector-efficiency of an actual airfoil can only be compared during simultaneous observations.

The meteorological conditions for icing are satisfied in the following ways: (a) In clear air, by freezing rain, radiational cooling in quiet air on exposed surfaces of grounded planes, and passing from a cold layer into a warm moist one; (b) in clouds, by convection at all levels, stratocumulus formed by turbulent mixing, orographic lifting over a mountain range or plateau, and by frontal lifting. Frontal action is the most extensive and the icing-hazard will vary widely with respect to time and distance from the front. As large frontal systems involve precipitation, the liquid water-content may be further modified by losses.

Air-masses vary considerably also in their icing-frequency. It was at first thought that this was due to their thermodynamic properties of moisture and temperature alone but Lacey recently showed that stability was a very important criterion. Moist air having a steep lapse-rate approaching the wet adiabatic was found to have the highest frequency of icing-reports. The present investigation verified this result and the additional comment might be made that the presence of a deep inversion above the unstable layer acts as an inhibitor.

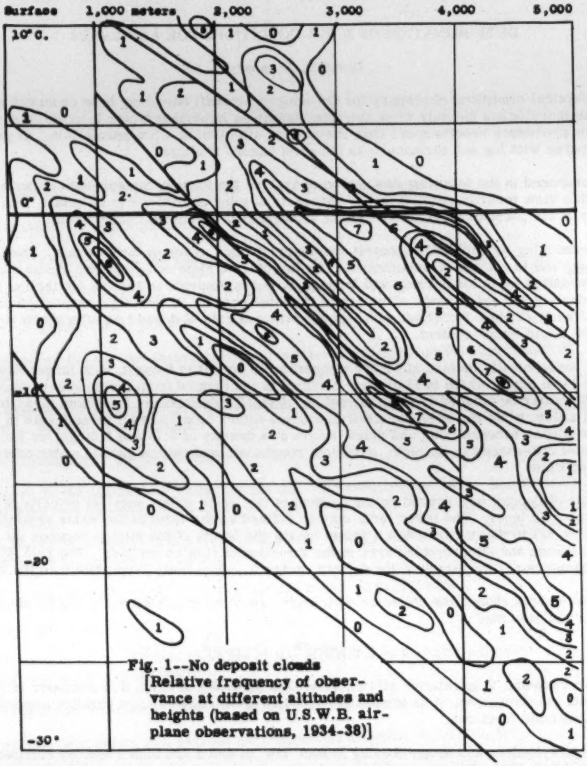

Fig. 1--No deposit clouds
[Relative frequency of observance at different altitudes and heights (based on U.S.W.B. airplane observations, 1934-38)]

Data from the airplane ascents made for the United States Weather Bureau between 1934 and 1938 gave the frequency of occurrence of no deposit, frost, rime, or glaze in clouds at below-freezing temperatures as indicated in Table 1.

Table 1--Variation of icing within air-masses

Type of air	No deposit reported in cloud	Frost	Rime	Glaze or clear ice
P_c	50	...	11	7
Npc	28	2	2	9
Pp	28	...	1	20
Npp	20	1	9	18
Tg	34	...	4	5
Ntg	...	...	...	...
Tp	2	...	2	...
Pa	1	...	...	6
Doubtful	22	...	1	5

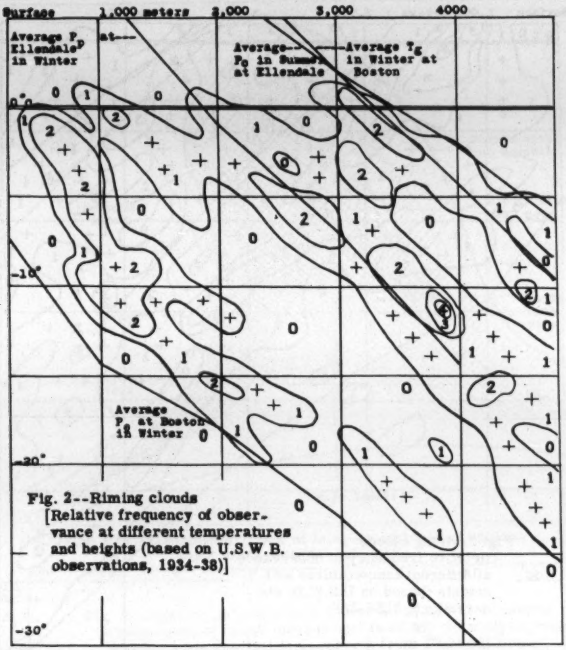

Fig. 2--Riming clouds
[Relative frequency of observance at different temperatures and heights (based on U.S.W.B. observations, 1934-38)]

The high icing-frequencies of the polar maritime air accounts for 68 per cent of the reports. As these air-masses are normally the least stable, the high lapse-rate of icing-clouds may be an associative rather than causative factor. In Figures 1, 2, and 3 are shown the frequency of occurrence of clouds of the no-deposit, riming, and icing types at different heights and temperatures. The comparison of the maxima with the average values in the different air-masses as given by Willett shows that the non-icing clouds are somewhat warmer than average and the glazing-clouds are somewhat higher and cooler at upper levels than normal, while riming-clouds occur mainly in those air-masses that have been strongly modified. These effects are shown most pronouncedly with wintertime Pp-air.

In spite of the fact that all air-masses, stations, and seasons were included in the same diagrams, there is a definite tendency for clouds giving a certain type of icing to have maxima at certain values of temperature and pressure. These maxima differ in location. It is believed that had sufficient data been used the icing-clouds could be shown to have lapse-rates significantly different from the non-depositing cloud. The analysis of the riming-data at Sonnblick substantiates this viewpoint and will be discussed below.

The relative frequency of icing with different frontal situations was studied using the 8:00 a.m. surface-maps following the airplane observations (APOB). The material agrees in general with previous correlations such as that of Minser. It was definitely noticeable that the icing-frequency was higher before than behind warm and cold fronts. No cases of glaze were reported in the warm sector and only four cases of rime were noted in the high clouds there. In a region ahead of the warm front where precipitation is heaviest, therefore, there will be no ice.

We may generalize the results as in Figure 4 to represent the icing-hazard about a storm-

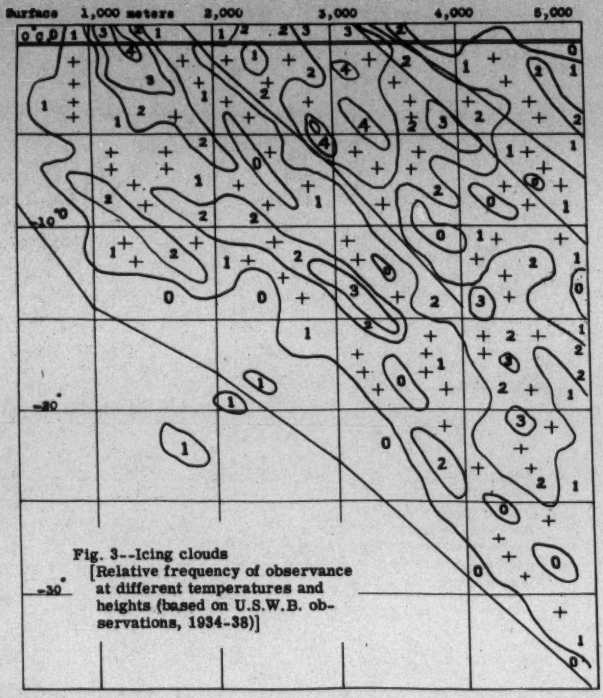

Fig. 3--Icing clouds
[Relative frequency of observance at different temperatures and heights (based on U.S.W.B. observations, 1934-38)]

area. The designations apply mainly to the higher clouds.

Life history of clouds--Clouds are dynamic units which are either actively growing or decaying but seldom static. The severity of the icing will depend on the liquid water-content and the latter will vary widely once the cloud has formed. Depending on the manner of cloud-formation, that is, convection, turbulence, frontal lifting, etc., it might be possible to estimate the amount of water-vapor that has been condensed at each level above the cloud-base from information gained from aerological ascents. Such procedure has been followed by Schirn and checked against Mt. Washington liquid-water measurements.

Clouds of liquid water cannot be regarded as stable colloids at below-freezing temperatures because of the losses due to crystallization and precipitation. There is as yet no criterion for determining whether a volume of saturated air will condense its excess vapor as ice-crystals or water-drops. The few ice-crystals that do form are extremely important and, as was first suggested by Bergeron, these must be present in a water-cloud to initiate heavy precipitation.

Icing and liquid water--Whatever precipitation, either as rain or snow, is measured at the ground, it represents a like amount that has been subtracted from the liquid water in the cloud. Other things being equal, the heavier it rains, the less dense the cloud becomes. It is believed that this relationship was first suggested by Learnard as a result of some (unpublished) measurements in 1939. The correlation between measurements of liquid water-content in clouds on Mt. Washington (elevation 6300 feet) and simultaneous precipitation at Pinkham Notch (2000 feet) about three miles to the southeast shows this inverse relationship. From the data in Figure 5 an

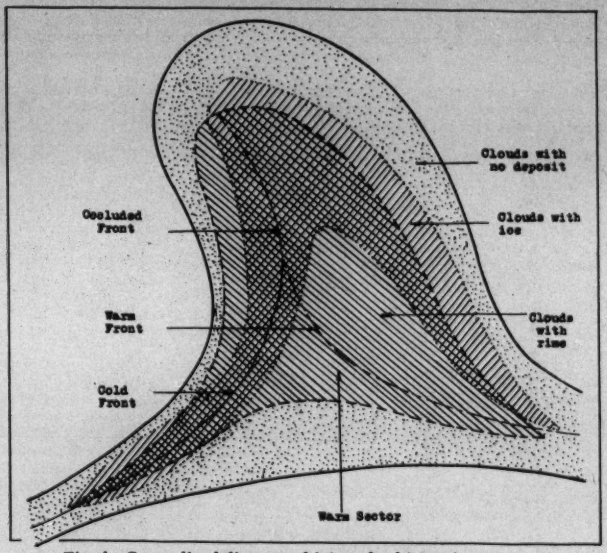

Fig. 4--Generalized diagram of icing-cloud types in regions about extra-tropical cyclones

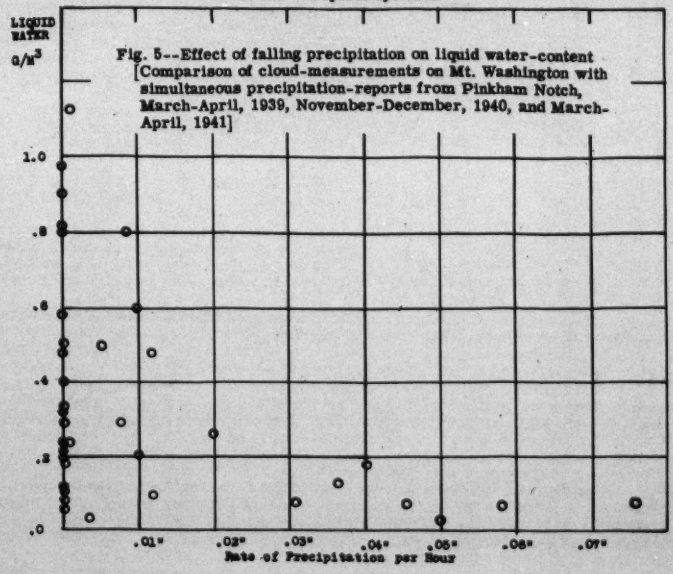

Fig. 5--Effect of falling precipitation on liquid water-content [Comparison of cloud-measurements on Mt. Washington with simultaneous precipitation-reports from Pinkham Notch, March-April, 1939, November-December, 1940, and March-April, 1941]

empirical rule might be established that no ground station reporting more than 0.03 inch steady precipitation per hour could have severe icing-conditions within the lower layer of clouds. The needed rate of precipitation might even be less at places with less pronounced orographic effects.

Individual storm-records mostly show the maximum liquid water-content just as heavy snowfall began, as illustrated by the record in Figure 6 of a storm on March 30, 1939, and the following precipitation-record of the two stations:

Mar. 30, 31, 1939, at	1:00 a.m.	7:00 a.m.	1:00 p.m.	7:00 p.m.	1:00 a.m.	7:00 a.m.
Mt. Washington	0.00	0.10	0.03	0.21	0.01	0.00 inch
Pinkham Notch	.....	0.02	.....	0.25	.....	0.05 inch

Previous authors have maintained that severe icing accompanies heavy storms but this can be true only at the outer margins. Large amounts of liquid water in deep layers represent an unstable condition that is easily destroyed. Coalescence as well as sublimation between cloud-drops and falling snowflakes will rapidly lower the liquid water-content. Evidence compiled from the United States Weather Bureau airplane ascents agrees with the view that precipitation depletes the liquid water.

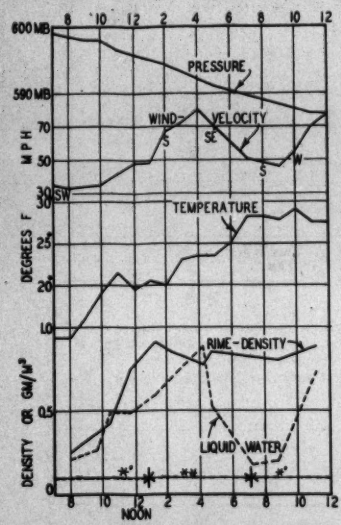

Fig. 6--Meteorological conditions during a warm-front passage, March 30, 1939, Mt. Washington, New Hampshire

Icing-probability and temperature--The reports on cloud-formations made by the pilots were tabulated so that the number of times a given temperature occurred in icing and non-icing clouds at all levels was obtained. The total number of observations at each temperature is plotted in Figure 7. It is a fairly constant curve until a temperature of -10° C is reached and then decreases rapidly in the interval to -30° C. Below it is the curve of the percentage of icing-clouds in the total. It is well to point out here that the distinction between ice and no ice in the reports were exceedingly arbitrary and rest entirely upon the pilot's skill and judgment. No distinction was made here as to icing-intensity or rate of accretion. Furthermore, there was a considerable tendency to cancel flights in heavy storms because of the danger to the plane.

The first feature that the percentage-curve presents is the irregular but definite increase at lower temperatures. While the chance of finding a cloud at all at temperatures below -15° C is small, the danger of ice in it is not diminished and flying in it should be avoided. The second feature is the minimum at -12°. At this temperature the difference between vapor-pressure of ice and water-surfaces is a maximum and sublimation will be most rapid. This may be also due to the propitious arrangement of the air-masses but, as it occurred with other sets of data, may be due to precipitation. The minimum at 0°C may possibly be due to a lag in thermal equilibrium of the plane as it ascends.

Due to the fact that clouds in the lower 2000 meters were mainly formed by turbulence and would have their maximum liquid water at the top, while high clouds formed by frontal lifting would tend to have a nearly uniform liquid water-distribution, the observations were then divided into two groups and the percentage-curves redrawn. The features for the higher and more numerous clouds are not reproduced as they only accentuate those shown in Figure 7. The percentage of icing-clouds was higher near 0°C.

Figure 8 for the lower clouds showed wider statistical fluctuations in number and percentage. It is difficult to state whether the tendency toward lower values between -7° and -16°C or the maximum beyond it is real. The fact that there is no definite minimum at -12°C might be expected because the low clouds do not yield large amounts of precipitation.

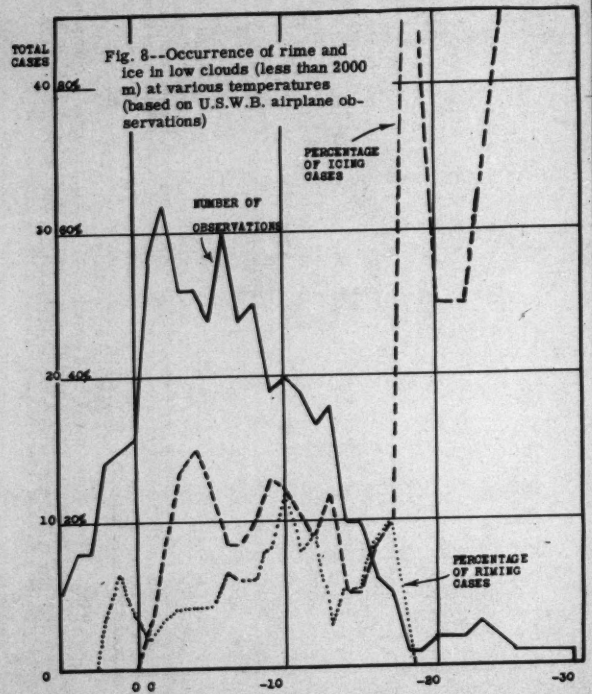

Fig. 8--Occurrence of rime and ice in low clouds (less than 2000 m) at various temperatures (based on U.S.W.B. airplane observations)

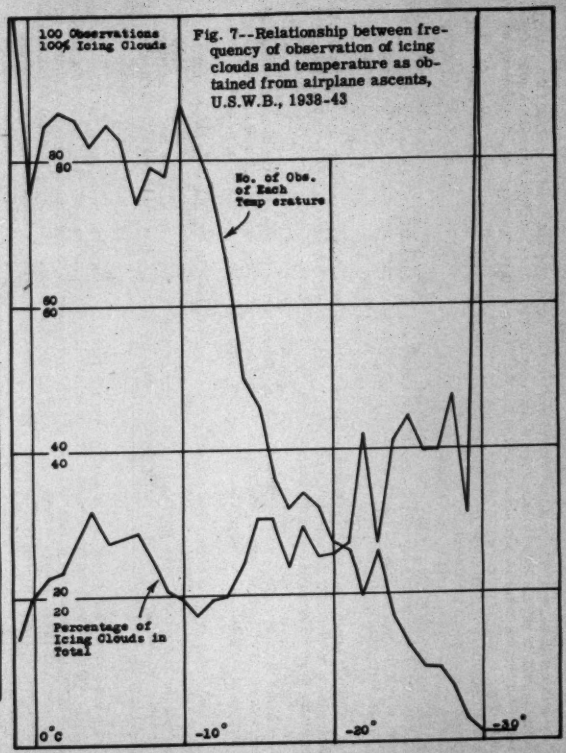

Fig. 7--Relationship between frequency of observation of icing clouds and temperature as obtained from airplane ascents, U.S.W.B., 1938-43

As most civilian flying, until a few years ago, was conducted below 2000 meters, the picture represented by Figure 8 is more indicative of most pilots' concept of the relationship between temperature and icing-hazard. Actually, in a cloud formed by pure convection, the higher and colder parts will have more liquid water. The danger of heavy icing has been partly offset by the low temperature and consequent formation of rime. With the high speeds of present-day planes, glaze may form as well as rime.

Relationship between temperature at the top of clouds and precipitation--In order to learn something of the life history of the clouds, the higher clouds were divided into four groups: (A) Non-precipitating, no deposit reported; (B) non-precipitating but icing; (C) precipitating and icing; (D) precipitating, but no deposit.

The following life-cycles may occur. When lifting is weak, the cloud formed has little liquid water even when of great vertical extent. No precipitation or deposits will be formed. The cloud may dissipate before going beyond the A-stage.

If the development is weak, with the passage of time precipitation can still develop without any increase in liquid water and, depending on the rate of sublimation, last until the cloud dissipates entirely or reverts to its initial state with no precipitation. The cycle would be A-D-A.

With more rapid condensation the weak A-type cloud develops into the B or non-precipitating icing-cloud with a high liquid water-content. When precipitation does begin, icing can still be severe for some time. Precipitation can continue because of sublimation after the liquid water has been reduced to the point where icing is no longer possible. The transitions in this cycle would be A-B-C-D-A.

Each group was divided into subgroups depending on the temperature at the top within a range of 5°C. Figure 9 shows a bar-graph of the number of clouds found in each interval of the group. The A-group, being the beginning and end of each cycle, should be the most numerous. This is so in general and the A-group exhibits an almost regular decrease in frequency with temperature patterned after those in Figures 7 and 8. The D-group with no ice or rime is constant at first, then shows a maximum as might be expected between -10° and -15°C followed by an irregular decline. The icing-clouds have a more even distribution although the numbers are fewer. The

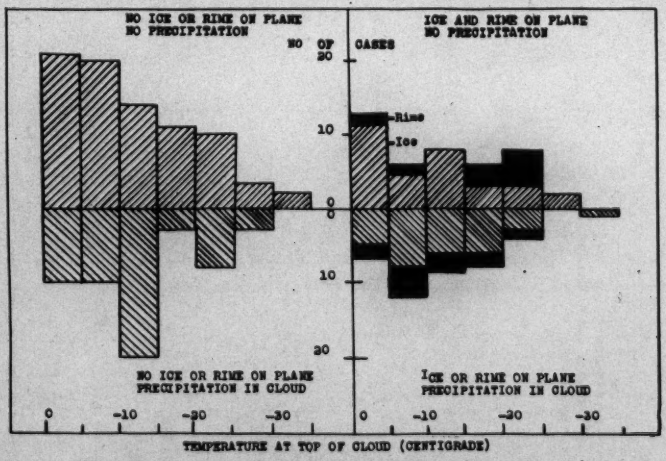

Fig. 9--Dependency of frequency of observation of rime, ice, and precipitation in high clouds and temperature at top of cloud (based on U.S.W.B. airplane-observational data)

non-precipitating ones have a maximum as before near the freezing-point followed by a nearly constant value. The precipitating ones have a slight maximum between -5° and -10°C. This could indicate that where the liquid water is high, precipitation could start as readily as with a high rate of sublimation in the D-type.

Similar interesting comparisons between the groups were made of occurrence and amount of precipitation at the ground and the influence of the temperature of the condensation-level.

Icing-hazard at selected mountain stations--Observations from a mountain offer many advantages as well as disadvantages over an airplane in flight. The advantages are the possibility of making extended observations of all meteorological elements, continuity of record, safety of observer, greater incidence of local cloudiness, and temperature-equilibrium of collector with air. The disadvantages are variations in liquid water, drop-size, and wind-velocity caused by topography, difficulty in correcting for wind-velocity, blowing snow under certain conditions, lack of range in temperature at some stations, and lack of suitable locations.

Intercomparison among the various stations is not readily feasible but long-term records provide a means of studying icing-situations at each location. Where permanent meteorological

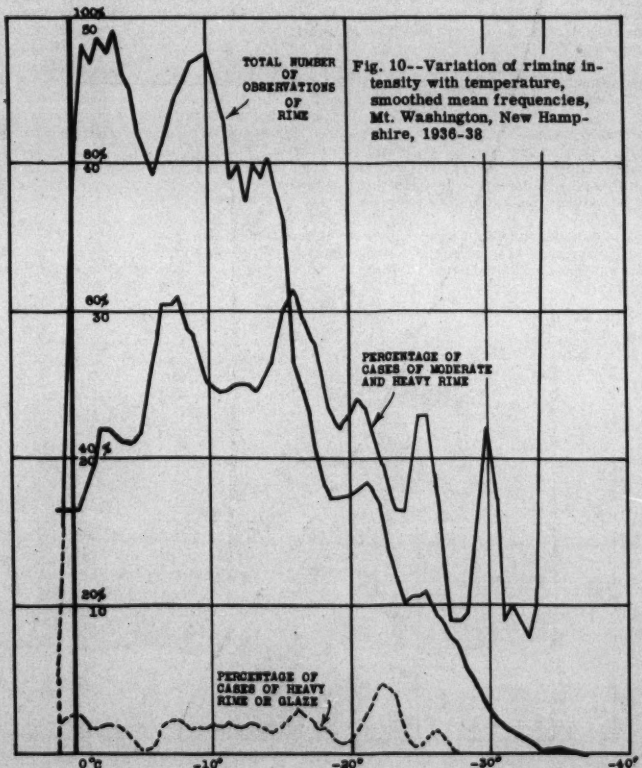

Fig. 10--Variation of riming intensity with temperature, smoothed mean frequencies, Mt. Washington, New Hampshire, 1936-38

stations are established, the possibility of including reports of icing-intensity for the information of pilots as a permanent service should be considered. A preliminary attempt of this nature was made in the season of 1939-40 on Mt. Washington but communication-difficulties prevented an adequate test being made. The reports were started again in January 1943 under the direction of Victor Clark, Ray Falconer, Kenneth Gould, and Manton Spear.

Mt. Washington observations--The riming-data were first examined to see if they contained minima corresponding to those found in APOBS. The observations consisted of eye estimates made four times daily in the four years 1936 to 1939. Entries were classified as being light, moderate, and heavy rime or glaze. The temperatures used were those at the time of observation and may have been several degrees different from the average of the six-hour period for rapidly moving fronts. Accordingly, the number of occurrences at each temperature were smoothed by means of the formula $N_c = [(a + 2b + 3c + 2d + e)/9]$. The smoothing produced an artificial extension of the observations to temperatures above freezing. No distinction was made for varying wind-velocities although this factor is of extreme importance.

The smoothed total number of observations on the accompanying graph in Figure 10 shows a broad maximum between 0° and -10°C. The drop at -5° may be real and due to a seasonal factor or the difference between the predominating Polar Canadian and modified Tropical Gulf air-masses. The majority of the individual monthly frequencies show this double peak although at varying places. Between -10° and -15°C the curve is very steep like that of the APOB-data, then flattens out with a number of minor peaks to zero at -35°. Rime has been observed on Mt. Washington at lower temperatures.

The second line gives the percentage of the total times of moderate and heavy riming-conditions. The values start from a minimum near 30 per cent and rise to a maximum of 62 per cent at -7°C. The major minimum at -12° can be ascribed to the depletion of liquid water by direct sublimation to the ice-crystals as for the case of high clouds. The minor minimum at -5° is similar to that found in low clouds. Following the minimum at -12° the percentage-curve has another maximum at -15° of 62 per cent and then falls away gradually to an average of 25 per cent. The general decrease is due to the increased lifting necessary to produce the same liquid water-content in comparison with higher temperatures.

To aid in understanding how precipitation is initiated, a check was made on the "ease of snowing" by counting the number of hours with snow on Mt. Washington in 1939 and 1940. Figure 11 shows the smoothed values. In addition, a smoothed graph of frequencies of daily mean temper-

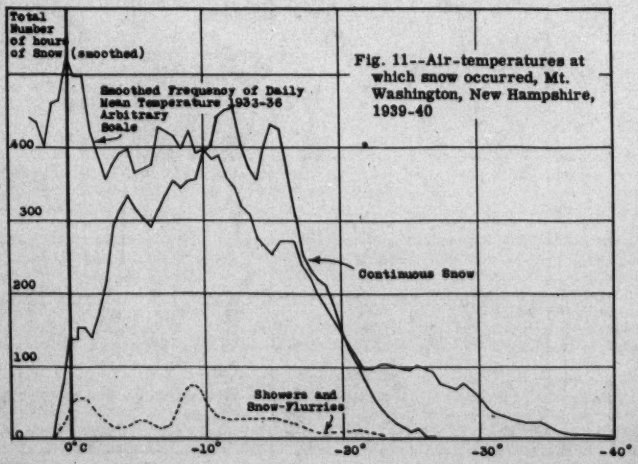

Fig. 11--Air-temperatures at which snow occurred, Mt. Washington, New Hampshire, 1939-40

ature for the four years 1936 to 1939 is given. The latter is by no means continuous but follows the characteristic values of the predominant air-masses. The highest percentage of snowfalls occurs well beyond -12°C due to the effect of local orographic lifting.

Tables summarizing the frequency of different riming-conditions for different wind directions are shown in Figure 12. In general, the heavy riming-situations occur with slightly warmer temperatures for southwest winds and slightly colder temperatures for the northwest winds, that is, the maximum icing is found in air not strongly modified after leaving its source-region.

Liquid-water measurements--Methods of measuring liquid water under riming-conditions have been developed and about six months of unpublished records were available. The smoothed values of the number of observations and liquid water are shown in Figure 13. These measurements showed the same general features as were discussed for eye observations, except that the general drop at 0°C is much stronger. Possibly a large portion of the liquid water freezes at that temperature.

Sonnblick Observatory--Sonnblick Observatory, Austria (latitude 47° 03′ north, longitude 12° 57′ east, elevation 3106.5 m), is one of the oldest and best known of the European stations. Its height is not extreme for the Alps but its location in Central Europe renders it free from the violent coastal storms of Mt. Washington. The rime is less frequent and the annual mean temperature of -6°C has not the extreme range. Few cases of glaze occur. Four years of published records, 1919, 1920, 1933, and 1937, were examined. It was necessary to make two separate compilations, one for east-southeast to west-northwest winds and the other for northwest to east winds, because of the marked contrast in air-masses at this altitude with wind-direction.

The southwesterly, heavily precipitating storms gave a double-peaked frequency-curve showing the winter and summer limits of mean temperature. Only one significant peak in the percentage of cases with riming-fog occurred at -8°C and the curve dropped uniformly at either side. The northerly wind-curve of fog-frequency versus temperature in Figure 14 was more irregular than that of Figure 15. The percentage-curve of riming had three, possibly four, peaks, one of which occurred at -12°C. Recalling the light precipitation-rates with these winds, this is not surprising. The tendency for increasing riming-rates at lower temperatures is well pronounced while the minimum near 0°C is not. The four peaks are caused by the winter and summer values of the predominant northern air-masses in Europe reaching Sonnblick while the southerly wind would bring air having characteristics derived over the Mediterranean and Tropics. The values agree well with those listed by Petterssen as characteristic for the altitude of Sonnblick derived from airplane ascents in Germany.

Figure 16 shows the relative number of cases of fog divided into the four groups A, B, C, and D used for the APOB-data. It is noteworthy that the peaks shift toward lower temperature as the magnitude of lifting, indicated by the amount of liquid water, is increased. Because of the sharpness of the peaks with northerly winds especially, forecasting of the icing-possibilities might be made with some precision if only the temperature and wind-direction were known at the flying level.

Nordenskiold, Spitzbergen--A valuable result of the International Polar Year was the establishment of a station at Nordenskiold (latitude 78° 10′ north, longitude 15° 26′ east, elevation 1049 m) from September 1932 to August 1933. The mountain is well within the Arctic Circle and exposed to moist air from the surrounding ocean and snow-fields. Eye observations of fog, rime and hoar, and glaze were made every two hours and copies of the original data published by Hilding Olssen.

No distinction was made here between entries of rime and hoar, although the former requires deposition of liquid water and the latter direct sublimation. Only entries which did include fog were thought to be possible rime-formations. Figure 17 gives the smoothed frequency of occurrence of fog at all temperatures as a solid line while the percentage of non-icing, rime and hoar, and glaze are given on a separate scale as broken lines. The first curve has several maxima with a pronounced one at -3°C due to predominant wind-directions and openings in the sea-ice.

The non-icing cases decrease rather regularly below 0°C and reach 0 per cent at -25°. The rate of glazing has a maximum at -4.5 and then decreased rather regularly. Whether the minimum at -13° is real and due to sublimation is not certain. The amounts of precipitation were exceedingly small. In spite of the difference in wind-velocity, the percentage of glaze alone is about as high as the icing-rate for the APOB-data to -16°. Because of the low elevation, the maximum available liquid water decreases rapidly with temperature. The percentage of rime and hoar

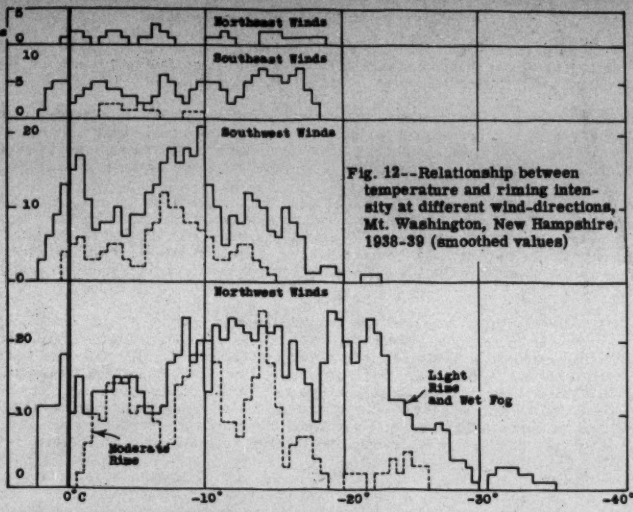

Fig. 12--Relationship between temperature and riming intensity at different wind-directions, Mt. Washington, New Hampshire, 1938-39 (smoothed values)

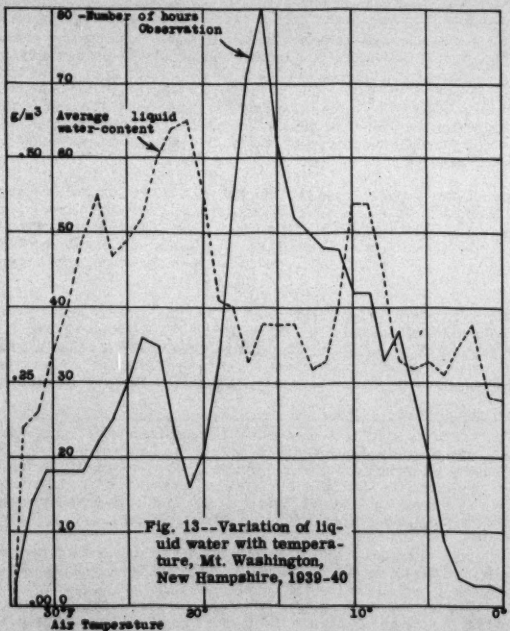

Fig. 13--Variation of liquid water with temperature, Mt. Washington, New Hampshire, 1939-40

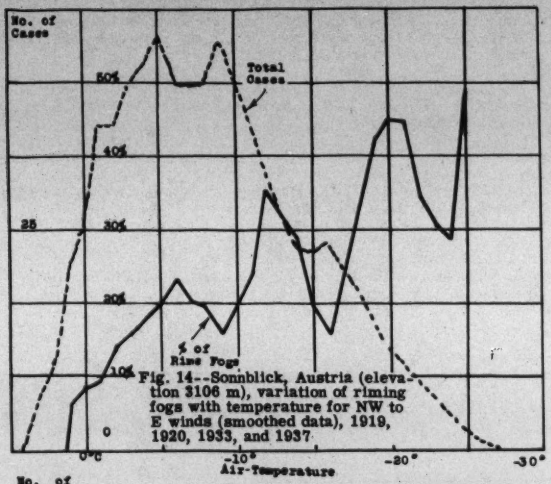

Fig. 14--Sonnblick, Austria (elevation 3106 m), variation of riming fogs with temperature for NW to E winds (smoothed data), 1919, 1920, 1933, and 1937

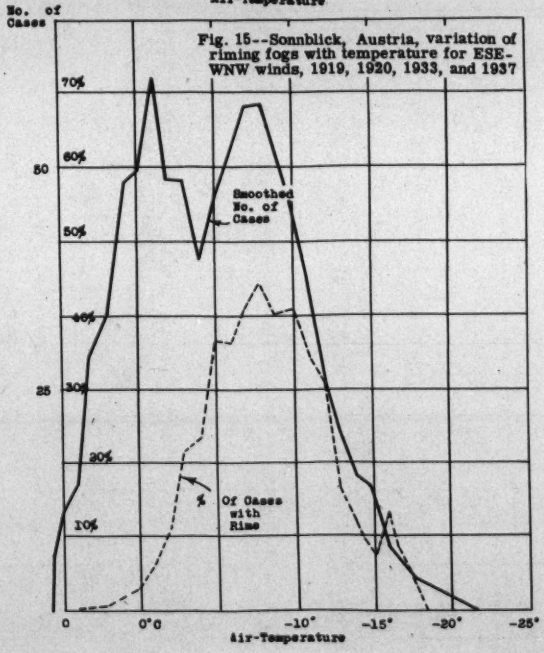

Fig. 15--Sonnblick, Austria, variation of riming fogs with temperature for ESE-WNW winds, 1919, 1920, 1933, and 1937

increases rather steadily to nearly a constant 100 per cent at the lowest temperatures and it is unfortunate that no distinction was made in the two forms in the records because of the bearing on the presence of sublimation and condensation-nuclei.

Collectors--As previously mentioned, the severity of icing varies not only with liquid water-content but with drop-size, relative velocity, and collector-size; the kinematic viscosity of air is a factor of nearly constant effect.

Measurements of liquid water are extremely difficult because the deposit changes the shape and collection-efficiency of the apparatus. On Mt. Washington, the technique of using a rotating cylinder that would preserve its shape while rime was deposited uniformly around it was adopted. The water deposited in a small interval of time would be

$$dW = 2\lambda\ PLrVdt = 2\lambda\ PLrdS \qquad (2)$$

where λ is collector-efficiency, P is liquid water in gm/m^3, V is (dS/dt), relative air-velocity perpendicular to collector, L is length of collector in cm, and r is radius of collector. This water will be distributed as a thin sheet of rime, dr thick, over the collector

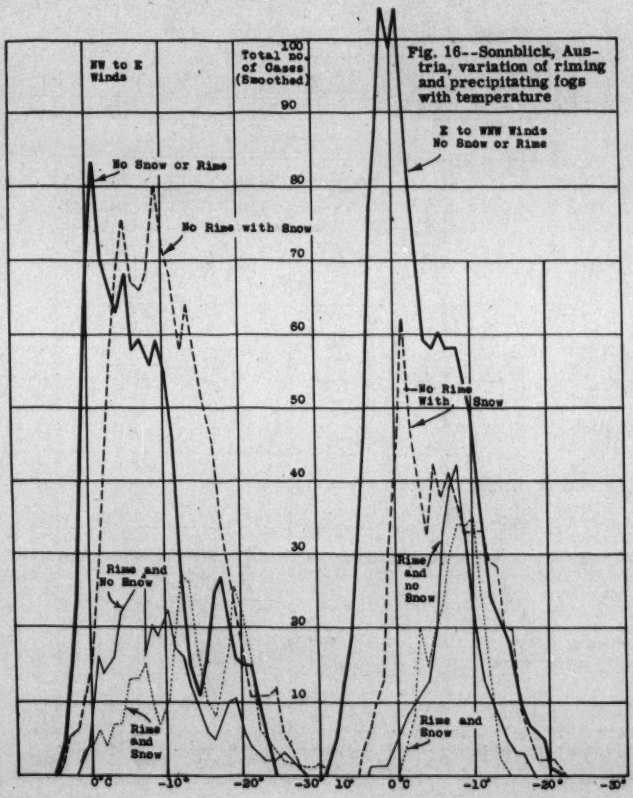

Fig. 16--Sonnblick, Austria, variation of riming and precipitating fogs with temperature

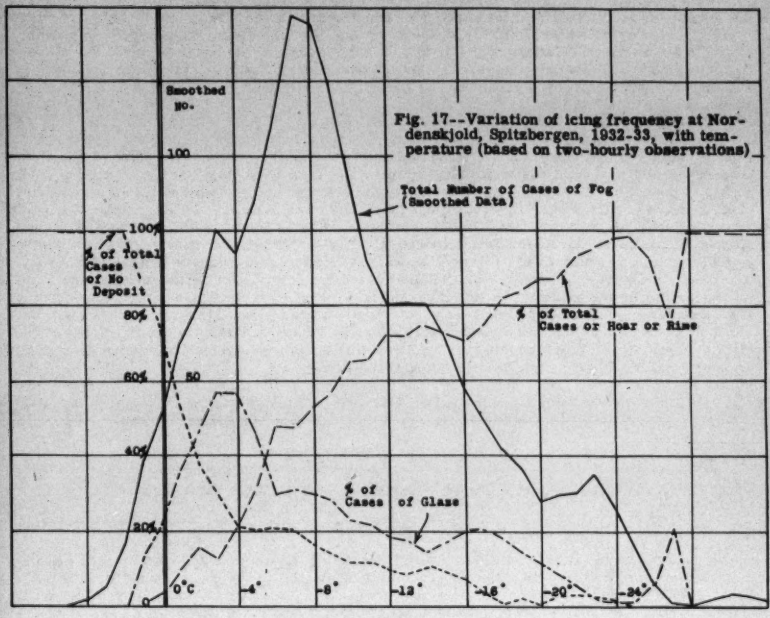

Fig. 17--Variation of icing frequency at Nordenskjold, Spitzbergen, 1932-33, with temperature (based on two-hourly observations)

$$dW = \rho dv = \rho 2\pi rLdr \tag{3}$$

where ρ is density of rime and dv is volume of increment.

Equating (2) and (3) and integrating with constant efficiency

$$dS = \pi \rho dr / \lambda P \tag{4}$$

$$\lambda PS = \pi \rho (r_1 - r_0) \tag{5}$$

or the increment in thickness is constant at high densities and efficiencies.

For very high velocities, large drops, and small collectors, λ, will be relatively constant. In practice, r_0, the initial radius, was kept less than one-eighth inch and with exposures lasting less than one-half hour r_1, the final radius, would not exceed one-half inch. The density also varied but by taking the average value and substituting in (5)

$$\rho \equiv \text{weight/volume} = [W / \pi L(r_1^2 - r_0^2)] \tag{6}$$

Substituting in (5)

$$P = [W/\lambda (r_1 + r_0)] = [0.49W/\lambda (d_1 + d_0)S] \tag{7}$$

$$P = [0.49/\lambda (d_1 + d_0)S] \tag{8}$$

The numerical value is for a sample ten cm long, weights measured in grams, diameters d_1, d_0 in inches, and air-flow in miles.

The air-flow was measured with standard Weather Bureau 3-cup anemometers which would

not usually ice too badly during the short run. The decrease in air-flow counteracted to some extent the errors in efficiency. Initially an average value of 0.50 for λ was taken which was later shown to be in error. Values nearer 0.80 to 0.90 would be more reasonable but observations to date were made with the old value for the sake of consistency. The lower value was necessary with measurements made at a station on the ground, but a shift to a higher station on a 30-foot tower was possible last year.

As the functional relationships of λ can not be derived analytically, an empirical method using a large number of cylinders exposed simultaneously was adopted. These were made of concentric wooden forms turned from one piece and ranging in size from about one-half inch at the top to five inches at the bottom. The spindles were mounted on bearings and provided with cups so that they could be turned by the wind. Tapered fittings permitted rapid mounting and dismounting during exposure. The forms were covered with brass or celluloid tubes divided into three rings. The middle one of exactly ten-cm length, whose weight and diameter were known exactly, was used as the collector, while the end ones of five-cm or more length were guard-rings to help maintain two-dimensional flow over the center. The celluloid was in many ways a better material to handle at low temperatures and to clean. Including the small collector on the anemometer, as many as eight samples were obtained at the tower- and ground-stations. Usually microphotographs of the cloud-drops were obtained with the equipment loaned by Professor Houghton for direct measurement of drop-size. It was hoped that the cylinders would allow a convenient method of measuring drop-size indirectly once the former had been calibrated.

Analysis of the data was made in the following way: Assuming that the variables in the equation may be arranged by some mathematical device such as Fourier series into separable functions

$$\lambda = C \cdot X(V^m) \cdot Y(D^{m+n}) \cdot Z(d^{-n}) \qquad (9)$$

where C is a constant and X, Y, Z are suitable functions. Then taking logarithms of both sides

$$\log \lambda = \log C + \log X + \log Y + \log Z \qquad (10)$$

we see that simultaneous observations at one station with constant velocity and drop-size will give us variations of efficiency with collector-size differing only by an additive constant for observations made at another velocity but with the same drop-size. This study is best carried out by plotting values of P from (8) against average collector-size on log-log paper. The slope of the curves will give the values of m and n. In the lower part of Figure 18 are given three pairs of such curves. It can be seen that in general the curves are similar and the one with the higher velocity can be superimposed on the others by a simple downward displacement. For the smaller collectors, P approaches a vertical limit asymptotically. The use of the average collector-size is

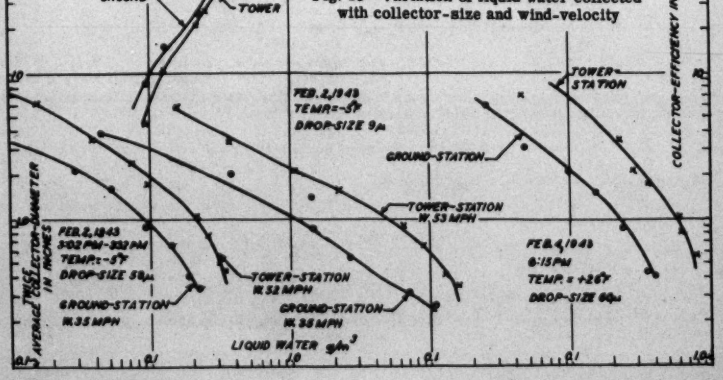

Fig. 18--Variation of liquid water collected with collector-size and wind-velocity

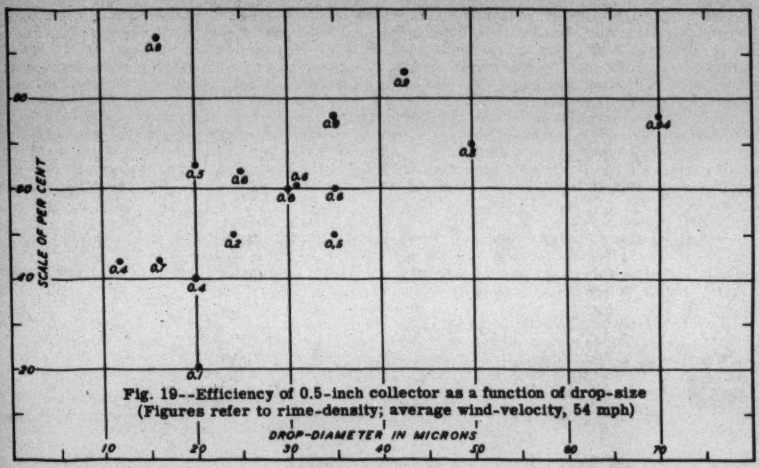

Fig. 19--Efficiency of 0.5-inch collector as a function of drop-size (Figures refer to rime-density; average wind-velocity, 54 mph)

not quite exact due to the large variations in diameter and λ, except for the larger sizes. The latter do not increase much. This part of the curve is nearly linear and the slope nearly the same for many curves.

For constant P and D, in the linear range

$$m \log (V_1/V_2) = n \log (d_1/d_2) \quad \text{or} \quad (m/n) = \log (d_1/d_2)/\log (V_1/V_2) \tag{11}$$

The ratios (m/n) varied between 1.5 and 2.0, the larger values occurring with smaller drops.

For constant V and D, the relationship is

$$\log (P_1/P_2) = n \log (d_2/d_1) \tag{12}$$

Values of n determined in this way ranged between 3.0 and 1.5 with the large values occurring with smaller drops.

If we assume that Stokes' law holds in the limiting case of large collectors and small drops

$$\lambda = (D^2V/9\mu d) \tag{13}$$

where μ is the kinematic viscosity of air, and the comparison of values for m and n is:

Item	Stokes' law Theoretical limit	Experimental values Large drops	Small drops
m	1.0	1.0 to 0.75	2.0 to 1.5
n	1.0	1.5	3.0
(m + n)	2.0	2.5 to 2.25	5.0 to 4.5
(m/n)	1.0	1.5	2.0

The weight collected during a given time may be derived from (2) and (13) as in (14)

$$W = \lambda PVdLt = (D^2VPV\,dt/9\mu d) = (D^2V^2\,LPt/9\mu) \tag{14}$$

The weights at one station on several occasions were constant, as required by (14), for all except the very large collectors, especially with large P- and D-values. Efficiencies greater than those given by (13) would require rising rather than falling collection-weights and the discrepancy is inexplicable as a straightforward hydrodynamic problem.

Attempts were made to determine the drop-size from the collection-ratios either by applying (13) or by empirical calibration from comparison-measurements on the microphotographs. Figure 19 shows the first-order approximations of the efficiency of a 0.05-inch collector as a function of drop-size. While there is a general correlation between large drops and high efficiencies, the scatter is beyond experimental error. The lower values of efficiency occur with low values of rime-density. The explanation to all the above apparently is that low-density rime formed by small drops or on large collectors during low temperatures is very weak and fragile and easily broken off by the wind. The same effect was noticed on stationary collectors of the same size-range. Apparently no system of collectors, rotating or stationary, can be devised to thoroughly eliminate this effect. It probably accounts for the absence of icing-reports at low temperatures rather than the lack of liquid water. Work has been started on measuring the structural strength of rime.

Density of rime--In connection with the problem of the density of rime, it is interesting to note that to a first-order approximation the density is independent of drop-size and only determined by the time-rate of deposit and temperature. A more extensive proof is available but space permits only the following outline.

A certain fraction of the liquid water is frozen on impact depending on the degree of supercooling. The remainder loses its heat of crystallization by conduction to the supporting surface, conduction to the air, and evaporation. If we assume the drop remains nearly in hemispherical form on contact with the surface which is a perfect conductor, and that the ice grows uniformly from this surface to the pole, the time taken for the drop to freeze will be

$$t_{cond} = r_1^2 \, (q - 0.5T) \, Dw/2T\theta \tag{15}$$

where r_1 = radius of drop, q = latent heat of crystallization, T = difference in air-temperature from 0°C, θ = thermal conductivity of ice, D = density of ice, ℓ = per cent of radius of hemisphere already frozen, and w = a slowly varying integral almost independent of r_1

$$= \int_0^{1.0} \ell \, d\ell / [(1 - \ell^2) + \ell/\pi \, (1 - \ell^2)^{1/2} \, (4.69 - \ell \, n \, r_1 \ell)].$$

In still air the rate of evaporation of water from a drop has been given by Houghton as

$$(dW/dt) = 4 \pi k r_1 (p_1 - p_2) = \text{rate of change of drop-weight} \tag{16}$$

where k = diffusion-coefficient of water-vapor into air, and $(p_1 - p_2)$ = difference in vapor-pressure between surface and at an infinite distance. The hemisphere formed by this drop would have a radius $\sqrt[3]{2}$ as big and could evaporate over only half the area, and consequently

$$(dW/dt) = \sqrt[3]{16} \, \pi \, k \, r_1 \, (p_1 - p_2) \tag{17}$$

The weight of water whose evaporation would freeze the drop is

$$dW = [q(1.333 \, \pi \, r_1^3)/(E - q)] \tag{17a}$$

where E is latent heat of evaporation. Equating (16) and (17) and rearranging, the time for freezing is

$$t_{evap} = \sqrt[3]{4} \, q \, r_1^2 \, (p_1 - p_2)/3(E - q) \, k \tag{18}$$

A similar expression can be set up for conduction-losses to air, in which r_1 appears as the square although this term is relatively small. The actual time needed to freeze the drop will be

$$(1/t) = (1/t_{cond} + 1/t_{evap} + 1/t_{air}) = (1/r_1^2) \, (1/C) \tag{19}$$

where C is a function of all variables other than r_1. In a moving air-stream the freezing-time of course will be decreased by a complex function of the air-speed, but if the boundary-layer is several times the drop-diameter, the function will depend on air-speed and not on drop-size. As the drops strike at random on the surface, we next wish to know the probability of one drop striking an unfrozen one and coalescing with it, since this is the factor determining the possibility of exclusion of air from rime.

The number of drops N deposited per cm^2 per second of radius r_1 will be

$$N = (\text{mass deposited/mass of one drop}) = [\lambda\ PV/(4/3)\ \pi r_1^3] \tag{20}$$

The area of the drop is $a = \pi r_1^2$, hence the total area is

$$A = Na = (3/4)\ (PV\lambda/r_1) \tag{21}$$

The product of the icing-time and the area covered per second gives the number of unfrozen drops at any given time. The probability that a given drop will strike this liquid water-surface and coalesce is given by the product of the respective areas

$$\Delta_2 = A\ (At) = (9/16)\ (\lambda PV/r)^2\ (r^2 C) = (9/16)\ (\lambda PV)^2\ C \tag{22}$$

A considerable advantage in the use of the product (λ PV) is that it is the time-rate of deposit of liquid water per cm^2 and it is unnecessary to know the values of any of its components. In preliminary work, the square root of the probability [Δ^2] was taken for convenience. Only the first term in C was used as the conductivity-losses are the greatest and the velocity-correction in the others are indeterminate. The results of plotting Δ against density gave the best agreement for densities below 0.5 gm/cc. It has been shown previously from the frequency-distribution of rime-densities that there is a transition in structure of air-inclusions from a simply connected type to a multiply-connected one at this density.

The upper part of Figure 18 where the density of the deposits is plotted against efficiency relative to the smallest collector at the higher velocity is of interest. Noting

$$\rho_a = (P_a S)/[\pi\ (r_2 - r_1)_a] \quad \text{and} \quad \rho_b = (P_b S)/[\pi\ (r_2 - r_1)_b] \tag{23}$$

where ρ is the density as before and the subscripts a and b refer to any two collectors exposed simultaneously, and λ is relative collector-efficiency = (P_b/P_a).

$$\left.\begin{aligned} \Delta \log \rho &= \log \rho_b - \log \rho_a = \log (P_b/P_a) - \log [(r_2 - r_1)_b/(r_2 - r_1)_a] \\ \Delta \log \lambda &= \log (P_b/P_a) \end{aligned}\right\} \tag{24}$$

whence the derivative

$$(d \log \rho / d \log \lambda) = 1 - \log [r_2 - r_1)_b/(r_2 - r_1)_a]/\log (P_b/P_a) \tag{25}$$

At extreme values the second term becomes unity as it tends to the form (0/0) and (∞/∞) at high and low ranges, respectively; in the middle range of pseudo-Stokes' law control, the numerator is nearly straight with a slope between 45° and 60°. The data for observations at the two stations coincide within close enough limits to justify (22).

Weather sequences--Of most interest to practical meteorologists is the possibility of utilizing the reports from Mt. Washington to forecast icing-conditions. While at present the location in the northeast corner of the United States and the low elevation of 6300 feet do not come within the range of many flights, studies of the developments there can be pursued with profit in analogous situations elsewhere. The following situation in March was chosen for detailed analysis because of the extreme and long-continued icing-conditions. Figures 20-a, 20-b, 20-c, and 20-d show the surface-maps of Eastern United States from $01^h\ 30^m$ March 10, 1943, to $13^h\ 30^m$, eastern standard time, March 12. The main feature was the eastward passage of the long trough almost parallel to the Allegheny Mountains off the coast, a situation which repeated many times. While cloudiness was widespread, the precipitation was for the most part extremely light. The upper winds showed a prevailing flow from the southwest parallel to the mountains and fronts. Figure 21 shows a sequence of RAOB-soundings taken at Huntington, West Virginia, which with a 24-hour displacement could almost be superimposed on those at Portland, Maine (Fig. 22). The main difference was the development of an inversion at the surface in the moist air moving north, and one somewhat below the level of Mt. Washington. Because of the motion upslope and adiabatic lifting, the mountain observations do not coincide with the RAOBS at the same level. At times this difference in temperature amounted to 10°C. The cloud-base could be found by tracing the pseudo-adiabatic curves downward until they crossed the RAOB. Usually the liquid water measured at the summit corresponded to the difference in q-values of the two levels.

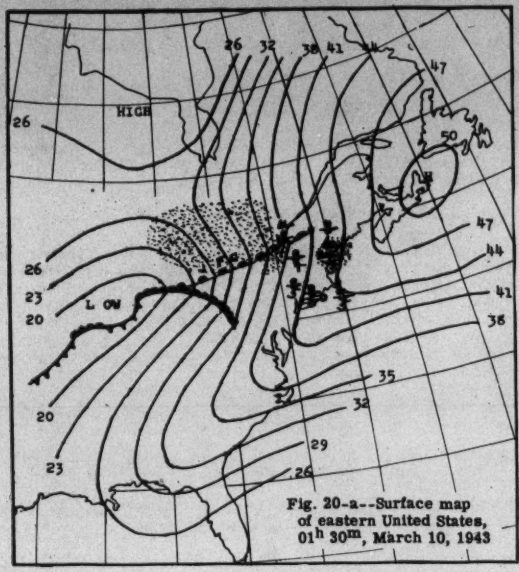

Fig. 20-a--Surface map of eastern United States, $01^h\ 30^m$, March 10, 1943

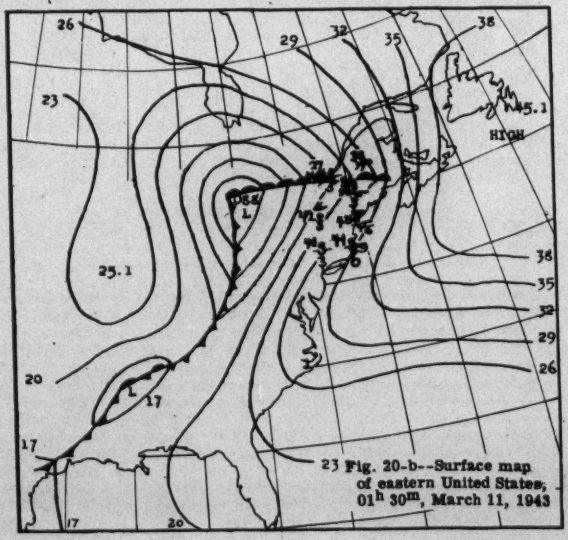

Fig. 20-b--Surface map of eastern United States, $01^h\ 30^m$, March 11, 1943

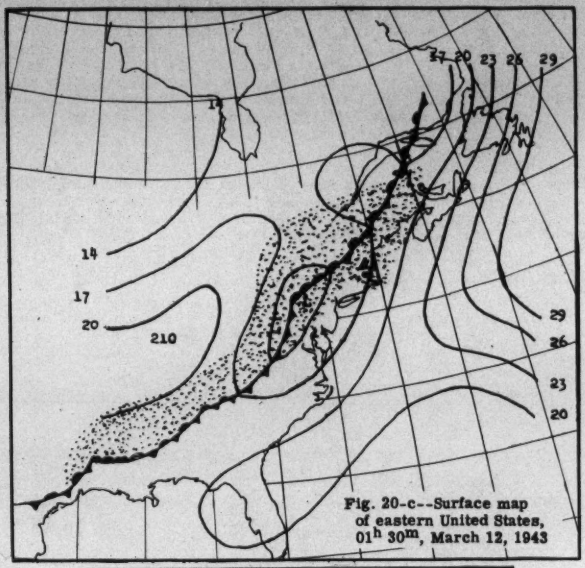

Fig. 20-c--Surface map of eastern United States, $01^h\ 30^m$, March 12, 1943

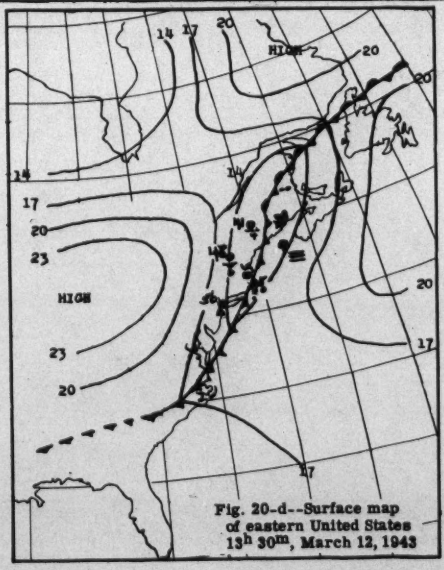

Fig. 20-d--Surface map of eastern United States $13^h\ 30^m$, March 12, 1943

Figure 23 gives detailed observations taken at three-hour intervals of weather and cloud-measurements. The drop-sizes were extremely large and characterized by a double-maximum distribution at times. This had been noticed by Houghton in the summer with the occurrence of precipitation. The most plausible explanation for the double maximum seems to be that the clouds, which may be formed at a distance by frontal action, are overlaid by another formed by forced ascent up the ranges. Lateral as well as vertical turbulence will mix the clouds which otherwise would have liquid water-contents and drop-sizes characteristic of the level of condensation. Microphotographs during the period are shown in Figure 24.

The study of the drop-sizes has been treated separately by Cunningham [Amer. Met. Soc., Washington Meeting, April 22, 1943] and the long series of data gathered by Falconer showed the drops varied between wide limits whose upper bound followed the vapor-pressure curve closely. Differences with air-mass types were closely associated with temperature although the summer-time measurements of Houghton gave a different range of values.

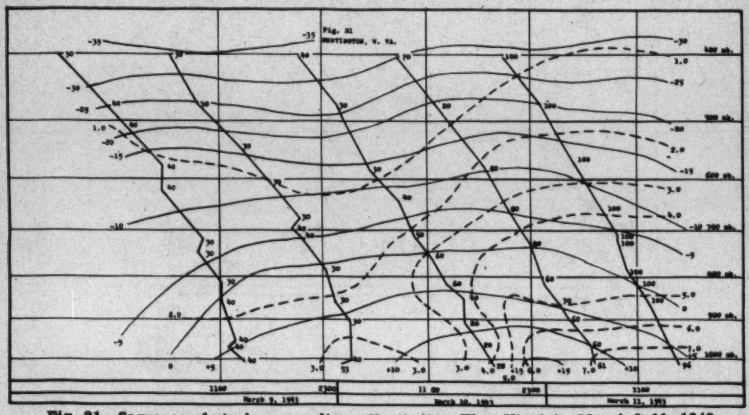

Fig. 21--Sequence of airplane soundings, Huntington, West Virginia, March 9-11, 1943

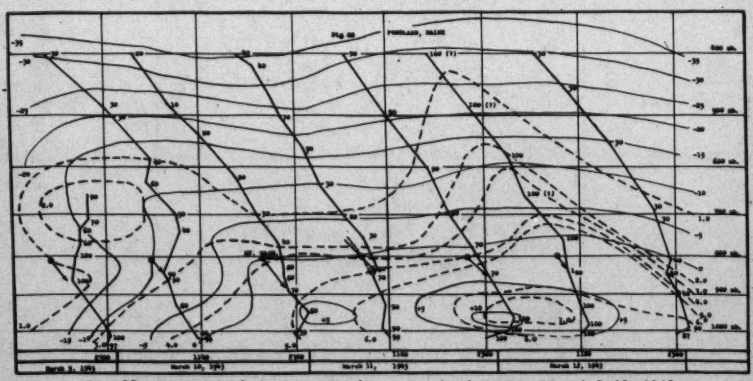

Fig. 22--Sequence of airplane soundings, Portland, Maine, March 9-12, 1943

The microphotographs also offer an opportunity to study the formation of crystals in the drops. Only at very low temperatures were particles visible which were definitely crystalline in outline and were frozen before contact. The supercooled drops maintained their round shape and many were unfrozen even after collection. A polarizing microscope was obtained to separate the frozen from the unfrozen drops and also the crystal-axes but, because of the small thickness of the ice, only the larger drops depolarized the light noticeably and no conclusion regarding the size of the crystals was obtained.

Three types of measurement of drop-sizes have been discussed and tried: The collector-method, as yet incomplete in theory and practice, yet necessary for application to airplane-structures; the microscopic, which is the most exact, yet relies on an extremely small sample from possibly a few hundred cc of air, is tedious to evaluate although visual methods of estimation are more accurate than the others; the corona-method is one of the oldest, yet has never been applied to the best advantage although it has the advantage of being fast and using a relatively large sample. For accuracy, a mercury-vapor H-4 lamp was used in conjunction with filters to isolate the 5461 Å line and get a monochromatic source. It was possible to observe sixth-order coronas with this lamp and even pulsations in diameter as the drop-size changed with gustiness. Micro-photometer-traces of these coronas taken by back-reflection have been made and by successive differentiation the drop-size distribution as well as maximum values should be obtainable. Com-

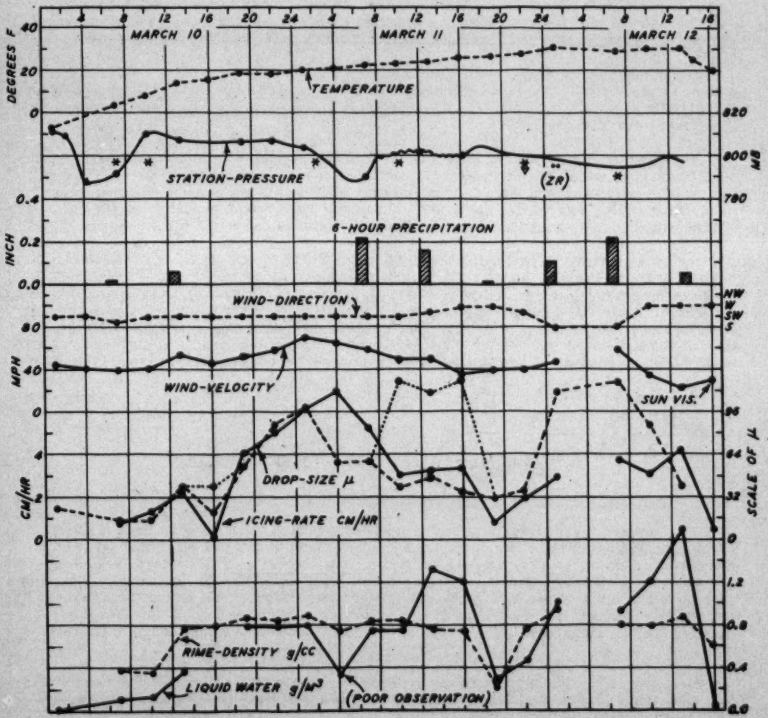

Fig. 23--Weather and cloud-measurements, Mt. Washington, New Hampshire, March 10-12, 1943

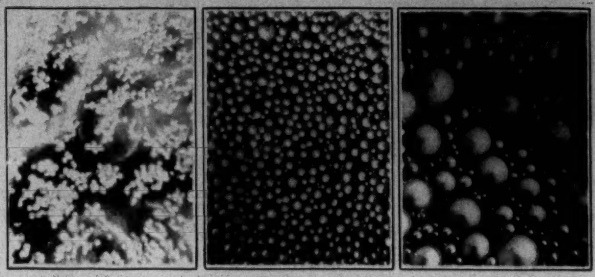

Fig. 24--Microphotographs of cloud-drops, Mt. Washington, New Hampshire, March 10-12, 1943
Left: $10^h\ 00^m$ a.m., March 10, snow and fog, wind SSW 42, temp. 7°F, 0.16 g/m^3, 20-μ drops
Center: $04^h\ 00^m$ a.m., March 11, fog, wind SW 76, temp. 25°F, 0.31 g/m^3, 75-μ drops
Right: $01^h\ 00^m$ p.m., March 11, snow and fog, wind WSW 51, temp. 29°F, 1.35 g/m^3, 60- and 140-μ drops

parisons with the microphotographs of radius from corona-measurements by eye show five per cent accuracy except when the distribution is broad and large drops are present.

In summarizing the work to date, the relationship between icing-frequency with weather elements has been investigated at various places. It has been shown that the icing-frequency does not fall off with temperature and also that increasing or heavy precipitation results in the loss of liquid water and icing-hazard.

Apparatus for measuring and collecting ice has been developed on Mt. Washington. The data show that loss of collection-efficiency by breaking off of rime is of considerable importance; studies of density have been made as well as liquid water and it is concluded that drop-size is of little importance in determining the density of rime while the rate of deposit is of great importance. Certain situations of weather have been studied and discussed to aid in forecasting icing.

In closing, I wish to take this opportunity to thank Dr. C. F. Brooks for his advice and interest in granting the opportunity to conduct this work; to express my appreciation to Professor H. G. Houghton for his invaluable criticism and counsel; and for the assistance, both financial and observational, rendered by the officers and staff of the Mt. Washington Observatory over several years of time. Among others of the Observatory staff, I am particularly indebted to Messrs. Patrick Harney, John Brown, Victor Clark, Raymond Falconer, Kenneth Gould, and Manton Spear, all of whom contributed observations under difficult conditions at the Observatory.

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INTERHOURLY VARIABILITY OF TEMPERATURE

V. Conrad

In the present paper rapid variations of temperature from one hour to the next at Mount Washington Observatory are examined [see 1 and 2 of "References", of which this paper is the continuation, at end of paper]. Two thresholds have been considered: Warmings (increasing temperature) and coolings (decreasing temperature) $\geq 3°F$ and $4°F$. (The amount of variation was taken from the hourly values in the tables of monthly temperature. This method is not exact. The difference should have been read from the thermograms. This procedure is, however, too wearisome for the present purpose. The errors of the simplified method do not influence the results adversely.)

The tables of hourly temperature of the Mount Washington Observatory for the years 1935 to 1937, tabulated and made available by the Blue Hill Meteorological Observatory, could be used owing to the kindness of Dr. Charles F. Brooks.

Table 1--Frequency of interhourly variations of temperature ≧ 3°F and 4°F, respectively, at Mount Washington, 1935-37

(c = coolings, w = warmings)

c = coolings w = warmings	Interhourly interval												Sum
	00-02	02-04	04-06	06-08	08-10	10-12	12-14	14-16	16-18	18-20	20-22	22-24	
°F						Fall							
c ≧ 3	5	5	7	(6)	6	6	10	7	9	5	9	4	79
c ≧ 4	2	3	1	2	2	3	4	3	4	2	5	1	32
w ≧ 3	4	3	5	(7)	(8)	14	8	3	1	3	2	4	62
w ≧ 4	2	0	2	(3)	5	8	4	1	1	1	1	1	29
						Winter							
c ≧ 3	14	14	14	13	17	15	15	22	19	15	15	16	189
c ≧ 4	5	6	7	(4)	(6)	9	7	6	10	4	9	8	81
w ≧ 3	16	14	12	15	(12)	8	13	8	8	13	16	13	148
w ≧ 4	7	7	5	(5)	(9)	4	4	5	4	4	5	7	66
						Spring							
c ≧ 3	7	10	10	6	4	8	13	16	7	11	9	10	111
c ≧ 4	1	5	1	1	1	2	8	5	1	3	3	4	35
w ≧ 3	6	9	24	35	37	10	8	2	2	2	4	4	143
w ≧ 4	3	7	9	12	11	3	5	1	1	0	1	0	53

The investigation in this paper is restricted to fall, winter, and spring, that is, September to May. In the 27 months of the three years, the temperature dropped and rose for at least 3°F from one hour to the next 730 times, and for the threshold of 4°F 297 times. These numbers alone show the great importance of the phenomenon. Variations of 3°F occur nearly daily, variations of 4° on two out of five days in fall, winter, and spring. Table 1 shows the two-hourly values of the frequencies of the coolings (c) and of the warmings (w) for the two thresholds 3° and 4°F.

Two-hourly values were chosen because only three years of observations were available and also for another reason. The statistics of the original tables show rapid risings of temperature crowded at 7 a.m. and at 8 a.m. The suspicion was strong that this phenomenon was caused artificially by the procedure of the observation. As I learned, the operator generally can not change the thermograph-chart within the shelter in consequence of the bad-weather conditions at the summit. He is obliged to take the instrument into the hallway of the Observatory. So the whole instrument is greatly warmed. Also, the cleaning of rime and snow from the instrument has similar effects. These manipulations take place between 7 a.m. and 8 a.m. Thus it was necessary to eliminate the data of these hours and to interpolate the respective numbers.

The corrected original hourly values give an opportunity to investigate whether or not the frequency of the rapid variations of temperature shows a consistent daily course. That would mean that the conditions of one part of the day are more conducive to rapid variations than another.

As is well known, Carl Abbe gave a criterion with which it is possible to investigate whether or not a series of measurements of one and the same quantity is systematically influenced. This is a frequent problem of many investigations in a physical laboratory because only non-influenced series yield useful results. In geophysics, often the reverse problem is of interest. An example is offered by the series of frequencies in question. If the criterion is not fulfilled, then a systematic influence could be assumed and the reality of a daily course is probable to a certain degree.

An expression (2A/B) is derived from the given series. If this fraction lies between certain limits depending only on number of elements of the series [see 3 and 4 of "References" at end of paper for further information], the criterion is fulfilled and no systematic influence may be assumed.

The limits for the series of 24 hourly values are $0.80 \leqq 2A/B \leqq 1.20$ and for 12 two-hourly values $0.71 \leqq 2A/B \leqq 1.29$. The results of the application of the criterion appear in Table 2 and can be summarized as follows: (1) The frequency of the coolings shows no real daily course in any season; (2) neither do the warmings have a daily course of frequency in winter; (3) the frequency of warmings shows a real daily course in fall and spring; (4) the indications of the criterion are identical for the frequencies derived from rapid temperature-variations ≧ 3°F and ≧ 4°F.

The rapid coolings are caused by advected air-masses piled up to the summit if mixing processes in the presence of intense inversions are disregarded. The cold heavy air-masses

Table 2--Abbe's criterion about the reality of a daily course of the frequency-curves of rapid temperature-variations

Season	Hourly values				Bi-hourly values			
	≧ 3°F		≧ 4°F		≧ 3°F		≧ 4°F	
	2A/B	Result	2A/B	Result	2A/B	Result	2A/B	Result
				Coolings				
Fall	0.722	No	1.157	No	0.846	No	0.834	No
Winter	0.937	No	0.801	No	1.406	No	0.73	No
Spring	1.178	No	1.045	No	1.23	No	1.03	No
				Warmings				
Fall	2.96	Yes	2.00	Yes	2.361	Yes	2.37	Yes
Winter	0.964	No	1.201	No	1.351	No	1.115	No
Spring	5.516	Yes	4.092	Yes	2.81	Yes	3.35	Yes

advance in any case and so the process is independent of the time of day. That is the meaning of corollary No. 1 (see p. 123).

The conditions of rapidly increasing temperature are more complicated. The pushing forward of the warm air and the removing of cold air-masses or the licking-up of the cold air, to use an expression of Max Margules, may be independent of the daytime as far as an abundance of energy exists. Further, the fact has to be considered that in winter generally the layers below the average height of the mountain ridge are stratified according to their specific gravity and that there are very stable conditions throughout the 24 hours. That seems to be the physical picture illustrating corollary No. 2 (see p. 123).

In fall and spring the content of energy is perhaps not so great on the one hand. On the other hand, stable conditions prevail during the night and unstable conditions during the hours of radiation. Unstable conditions favor the invasion of warm air. Stable layers are eventually passed over by the warm air which does not reach down to the summit. So corollary No. 3 (see p. 123) can find its explanation.

In Table 3 are presented the percentages of the rapid temperature-variations which occur between 6 a.m. and 6 p.m., the average hours between sunrise and sunset.

These statistics strengthen the conclusions drawn from the indications of Abbe's criterion. The uniform distribution of coolings in the 24 hours in the three seasons and of warmings in winter, as well as the greater probabilities of rapid warmings during daytime in fall and spring, are illustrated in a conclusive way. (In spring the frequencies of the warmings are surprisingly crowded between 4 a.m. and 10 a.m.; this phenomenon has not yet been explained.)

The average value of the temperature-difference between two consecutive hours is 4°.10 F if variations ≧ 3°F are considered and warmings and coolings are combined. The arithmetical mean of the coolings is 4°.15 F and of the warmings 4°.05 F.

A discussion of the daily course of these differences is not intended but the average amounts during night-time (6 p.m. to 6 a.m.) and during daytime (6 a.m. to 6 p.m.) are of interest. We get the following values:

	Night-time °F	Daytime °F
Coolings	4.15	4.15
Warmings	3.80	4.30

This is in close harmony with the earlier results. The average value of the coolings is independent of the time of day. The warmings are not only more frequent but also more intense during daytime.

One could easily believe that the periodical heating and radiating process could contribute a considerable part to the inter-hourly differences ≧ 3°F. This objection

Table 3--Frequency-percentage of rapid temperature-variations during daytime (6 a.m. to 6 p.m.)

Season	Cooling or warming	Frequency-percentage for	
		≧ 3°F	≧ 4°F
Fall	c	56	56
	w	66	76
Winter	c	53	52
	w	43	47
Spring	c	49	51
	w	65	63

seemingly does not hold because the periodical interhourly differences surpass 1°F (on the average) only little on the one hand. (John S. McNair and Victor F. Clark derived the mean daily courses of the single months from the continuous records at the Mount Washington Observatory. The manuscript is deposited at the library of the Blue Hill Meteorological Observatory.)

On the other hand, rapid changes of temperature are generally accompanied by high cloudiness and strong winds, so the effect of the direct incoming and outgoing radiation may be suppressed still more.

The greatest interhourly coolings within the three years were 12°.0 F (February 14, 1937, 12 p.m.). The greatest warmings were 9°.1 F (November 14, 1937, noon) and 10°.7 F (March 29, 1936, 1 a.m.).

Finally, it is noticeable that the coolings nearly equal the warmings, with respect to number and amount. Thus the rapid variations of temperature do not disturb the general heat-balance. This important result is in best agreement with a former investigation [2] in the interdiurnal variability of temperature.

Conclusion--Coolings and warmings of $\geq 3°F$ and $\geq 4°F$ happen nearly every day and on two out of five, respectively, at Mount Washington in fall and in winter and spring.

It is shown that the periodical heating-process does not essentially influence the rapid interhourly variations of temperature $\geq 3°F$. The latter represent, therefore, the effects of advected cold and warm air-masses.

The times of occurrence of coolings are independent of the time of day.

The same can be proved for warmings in winter.

The probability of rapid warmings is greater during daytime in fall and spring. The reason of this phenomenon has to be seen in the instability of the atmosphere in these hours.

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FREEZE-AND-THAW FREQUENCIES IN THE UNITED STATES

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Introduction

The accompanying map (Fig. 1) shows the distribution of effective freeze-and-thaw alternations per year over the United States. It is based upon observations of maximum and minimum temperature made by cooperative observers of the United States Weather Bureau at 863 stations during the 18 years 1914-31, representing a total of almost ten million individual thermometer-readings. It is presented primarily as a statement of distribution of a single factor that must be considered when climatological problems confront the engineer, agriculturalist, geologist, geographer, economist, or others concerned with temperature-changes.

Effective freeze and thaw

While it is an easy matter to determine temperatures of the air and those at slight depth

Fig. 1--Isarythmic chart of the United States

within the soil, it is extremely difficult to measure the temperature of the soil-surface itself. The surface-temperature is subject to much more rapid and to wider variations than is that either above or below, where determinations are ordinarily made. The only data available in sufficient numbers for distributional studies are those taken in standard instrument-shelters at a height of five feet above the surface. Temperatures thus determined fail, often by rather notable amounts, to exhibit the extreme variations experienced at the Earth's surface.

For the ground to freeze something more is required than a short drop in temperature to below 32°F. There is a duration-factor as well. From many standpoints the effect of lingering temperature barely below freezing is the same as a much more pronounced drop of short duration. The observations made by cooperative observers ordinarily involve a single reading of maximum and minimum thermometers each 24 hours. From these it is often impossible to know much about the duration of any particular low temperature, or the exact number of times the temperature has actually fluctuated past any particular point that might be regarded as critical. Such limitations render it impossible to determine precisely the entire number of times that temperatures fluctuate above and below freezing during the year. The number of alternations between freeze and thaw at the ground-surface is even less determinate.

The standard air-temperature of 32°F is not a good criterion of effective freeze in terms of such a process as rock-weathering. Air reaching the bulb of a thermometer in an instrument-shelter is ordinarily warmer than that immediately in contact with the ground and it may be either notably warmer or colder than that a short distance within the soil. When 32°F is reported as a minimum temperature for a particular day the chances are strong that it represents a freeze of only short duration, one not likely to form ice on pools or interstitially below the surface. From the biological viewpoint the concept "killing frost" is similar in many respects to that of "effective freeze" at the surface. It is somewhat easier to observe, however, as the effects on vegetation are evident enough. Under ordinary conditions a short drop in temperature to 28°F constitutes a killing frost, but several hours in the range 28-32°F may be equally effective. The former condition is ascertained readily from records of cooperative observers; the latter is not. With such considerations in mind it was decided that for the purposes of the present study each drop in temperature to 28°F, or lower, be considered as evidence of an effective freeze at the surface. It appears reasonable to believe that the number of cases in which temperatures that low fail to be ef-

fective in freezing the surface, for the reason of insufficient duration, will be offset by about a similar number of cases in which prolonged temperatures between 32°F and 28°F are thus effective.

For an effective thaw the temperature must rise at least to 32°F and remain above freezing long enough to melt surface-ice. To effect complete melting the duration may vary on up to days or even months. Melting does not occur simultaneously in all parts of a frozen layer. It occurs first around the margins of surface-pools and at interstitial-contact surfaces. Once it has progressed to the point where a subsequent freeze will permit new expansive growth of ice, the thaw is effective as far as such processes as rock-weathering are concerned and this condition follows soon after surface-temperatures rise above freezing. Standard air-temperatures may lag behind surface-temperatures. When, during rising temperatures, 32°F is reached five feet above the ground the surface itself may be considerably warmer. Under such conditions an effective thaw has been experienced. With such considerations in mind it was decided that for purposes of the present study each rise in temperature to 32°F, or above, be regarded as an effective thaw at the surface.

In making the frequency counts indicated on the accompanying map (Fig. 1), the daily temperature-records of a station were followed through the period under consideration and each rise to 32°F following a drop to 28°F, or less, was counted as a single alternation between effective freeze and thaw. If experience should require modification of these critical values there would follow some change in the actual number of alternations per year. It is improbable, however, that the trends of isarythms would show appreciable change. Areas of highest and lowest frequencies would occupy about the same positions, and gradients between them would be similar to those shown on Figure 1.

Basic data

The temperature-observations upon which this study is based are those published in "Climatological data" (published 13 times a year, monthly and annual summary, by the United States Weather Bureau, Washington, D. C.) for 18 consecutive years beginning in 1914. As far as possible country stations, operated by cooperative observers, were selected. The distribution of cooperative observers, however, depends on such factors as the availability of men who are willing to assume the task and quite closely follows rural population-density, so that it is almost inversely proportional to the interests of students concerned with such things as rock-weathering. An attempt to keep the final map balanced from the standpoint of station-distribution led to the exclusion of many stations with excellent records. There would be no particular advantage, for example, in subjecting about 100 stations in the Great Valley of California to frequency-counts, tabulations, and averagings, requiring the expenditure of more than 200 hours of work, if within all mountainous parts of that State fewer than a dozen stations had continuous records.

Difficulties were encountered, especially in Western States, in finding stations with 18 years of consecutive observation, a matter of 13,148 thermometer-readings. Several types of incomplete record could not affect the present study. The absence of minimum temperatures during an interval when the maximum at no time reached as high as 32°F, or the corollary condition, when all minima are above 28°F, introduces no real significant break in station-records. The absence of records in summer for stations below 4000 feet in elevation is of no concern. In comparatively flat regions short gaps in station-records may be filled with confidence if several nearby stations kept above the daily minimum of 32°F, or the daily maximum of 28°F. Imperfections of records of these types were not regarded as significant breaks in continuity.

As a rule, the stations with perfect records are those in cities, where thermometer-exposures are such that they are least suited for the requirements of the study. It was found possible to omit practically all city station records east of the Rockies, but in the Far West the spaces between stations were in many cases so great that some had to be included. The geographical distribution of stations actually used is shown on the map (Fig. 1).

Over 1200 stations were originally selected for inclusion in the study. An examination of their records indicated that only 28 per cent had an absolutely unbroken series of observations extending through 18 years. Table 1 indicates regional reliability of records for the 863 stations actually retained out of the original 1200 and used in compiling the map of Figure 1.

Of the 863 stations 336, or 39 per cent, have perfect records for the entire 18-year period. Sixty-eight per cent have perfect records for 16 or more years, and 84 per cent for 14 or more years. About 13 per cent have perfect records for only from 9 to 13 years, and 3 per cent from 6

Table 1--Number of stations with perfect records of indicated lengths in various parts of the United States

Division	Length in years of perfect record													
	18	17	16	15	14	13	12	11	10	9	8	7	6	Total
New England, New York	21	4	4	1	4	2	4	1	1	0	1	0	1	44
New Jersey, Delaware, Pennsylvania, Maryland, Virginia	21	15	8	6	5	2	4	1	1	0	1	0	0	64
West Virginia, Ohio, Indiana, Kentucky	18	21	18	6	8	4	1	0	3	1	3	2	1	86
Michigan, Illinois, Wisconsin	29	21	8	10	2	1	4	1	1	1	0	0	0	78
Minnesota, Iowa, Missouri	22	9	9	4	4	1	4	0	0	1	2	1	0	57
North Dakota, South Dakota, Nebraska, Kansas	23	13	6	10	8	5	2	0	3	1	1	1	0	73
North Carolina, South Carolina, Georgia, Tennessee	27	18	9	8	8	4	0	1	3	1	1	0	0	80
Florida, Mississippi, Alabama, Louisiana	42	15	7	6	2	2	2	0	0	0	0	0	0	76
Arkansas, Oklahoma, Texas	37	6	13	6	2	5	5	2	0	3	0	1	0	80
Colorado, Utah, New Mexico, Arizona	12	8	4	10	5	4	5	9	2	0	0	2	1	62
California, Nevada	24	3	3	0	2	0	1	3	0	3	0	2	2	43
Washington, Oregon	32	4	3	5	2	2	2	0	0	0	0	2	1	53
Montana, Wyoming, Idaho	28	13	5	2	5	4	1	2	4	2	1	0	0	67
Totals	336	150	97	74	57	36	35	20	18	13	10	11	6	863

Table 2--Cumulative averages, frequency of effective freeze and thaw, for intervals of from one to 18 years, beginning with 1914

Year	McMinnville, Oregon	New Meadows, Idaho	Berthold Agency, N.D.	Eastport, Maine	Roswell, New Mex.	Plain Dealing, La.	Gainsville, Fla.
1914	17	164	95	66	63	30	2
1915	15	155	93	62	67	27	1
1916	21	158	92	55	65	28	2
1917	22	157	94	52	67	29	3
1918	22	160	96	51	65	30	5
1919	22	164	94	53	66	29	6
1920	25	165	95	51	67	28	5
1921	24	164	93	51	66	26	4
1922	25	163	92	51	66	25	4
1923	25	161	94	50	63	24	4
1924	25	161	94	50	65	25	4
1925	23	159	95	51	66	25	4
1926	22	156	95	52	65	25	4
1927	22	154	94	52	64	25	4
1928	22	153	96	53	64	25	4
1929	24	154	96	53	66	25	5
1930	24	153	96	53	66	26	4
1931	24	154	98	53	65	25	4

to 8. Sectional reliability, as indicated by percentage of perfect records of 14 or more years, varies from a high along the eastern Gulf States, where only 5 per cent of records less perfect, to a low in the Southwest and Mountain States, where 37 per cent are imperfect for 14 years. In the average of all sections 18 per cent of the stations used in this study have perfect records for less than 14 years.

From the data above it was apparent that a choice had to be made between mapping the United States on the basis of 336 perfect-record stations and the alternative of using many stations with less continuity. Before making this decision tests were made to determine the probable accuracy of shorter records.

Twenty-four stations were selected from widely scattered parts of the United States and cumulative averages were computed for each on records of from one to 18 years. The results for a representative seven are tabulated in Table 2. In each case the top row of figures is the frequency

of alternations between freeze and thaw for the year 1914, the second is the average between the counts for 1914 and 1915, and so on to the basal row, which is the cumulative average for all 18 years.

McMinnville, Oregon, ordinarily proves to be an erratic station in climatological investigations and was selected for that reason. In 1917 it experienced 17 alternations between effective freeze and thaw, a departure of -7, or 29 per cent, from its 18-year average. The following year witnessed even fewer alternations, dropping the cumulative average to 15, a departure of -9, or 37 per cent. After the third year of record, however, the departure in no case exceeded 3, without regard to sign, and after the sixth year remained 2, or less. There is thus little to choose between the cumulative averages of any year beyond the sixth.

New Meadows, Idaho, was selected because of its high frequency of 154 alternations in the 18-year average. Only the seventh year shows a departure of more than 6 per cent from that of the entire period. Eastport, Maine, is the most erratic maritime station included in the study. In 1914 it departed by +25 per cent from its 18-year average. The coincidence that two years of very high frequency were followed by a year of very low reduced all departures to less than 6 per cent after the second year of record. Roswell, New Mexico, at no time departed more than 5 per cent from its 18-year average for the reason that both 1914 and 1915 happened to approximate the average. The low-frequency Florida station varies widely in terms of percentage in its earlier years, but the numerical values are too small to be significant. There is actually little difference in any of the cumulative averages beyond the third year of record.

As a result of the study just outlined the conclusion was reached that it would be desirable to use records from stations having fewer than 18 years of continuous record rather than sacrifice distributional detail.

Experimentation also demonstrated the possibility of supplying some missing records on the basis of nearby stations. This procedure was followed only in the case of a few stations in the Far West. It was used only for short breaks, three days or less in length. The records of nearest stations most closely paralleling the station in question on other days were substituted in the breaks, provided that they departed by 3°F, or more, from either of the critical values, 32°F or 28°F. The accuracy of the study could in no way be affected by this manner of adding distributional detail.

Cartographic representation

Frequency-counts of alternations between effective freeze and thaw for the 863 selected stations were entered in proper positions on a relief-map of the United States to serve as controls for isarythmic representation. Three classes of stations were designated by symbols, those with 14 to 18 years of continuous record, those with 9 to 14 years, and those with 6 to 9 years. Over 84 per cent of all records fell into the first class and were considered as exhibiting no significant departures from 18-year averages. The intention behind the matter of so classifying the various stations was that of discounting short-record stations where found to be at variance with those in the surrounding territory. As a matter of fact, very few cases of this kind were found and it was possible to draw isarythms that agreed with 98 per cent of all records used. Every case of disagreement was in the direction of the station in question exhibiting fewer alternations than the area in which it is mapped and all appear to be the result of improperly exposed thermometers. Many city stations have records that depart as much as 20 per cent below frequencies of the territory in which they are located. No country station has been found that departs as much as ten per cent.

Frequency-averages vary from zero for many coastal stations, and a considerable area in southern Florida, to 188 at Fraser, Colorado. To represent these in terms of an isarythmic interval of 10 would require the differentiation of 19 separate fields. In general, coastal fields would be wide in non-mountainous regions, while in the highly diversified relief of the interior as many as 12 isarythms would be necessary between some adjacent stations. Detail in coastal regions would be suppressed so as to erase information readily available in the records, whereas personal judgment would be demanded in rough inland areas beyond all reasonable limits of error. A map constructed on this basis would appear most detailed where actually most inaccurate. The choice of a larger interval, such as 25, would reduce the number of fields to reasonable limits but would still further reduce its value along coasts and in regions of slight relief. The nature and distribution of the basic data in this case demand the selection of a progressively widening interval for cartographic representation. Of the several possibilities of widening isarythmic intervals, the one apparently best suited to the needs of the present study, and therefore adopted, is based on

a progressive series of fractional parts of the year. The highest frequency-field is the area in which alternations between effective freeze and thaw occur, on the average, as often as one-half of the days in the year. The next field shows frequencies of between 1/2 and 1/4 of the days of the year and is followed by the 1/4 to 1/8 field, and so on down to the final grouping of less than 1/128. This arrangement requires the differentiation of but eight fields, a reasonable cartographic venture, and it emphasizes detail in parts of the map where basic data are most numerous and accurate, while blanketing areas least covered in the records. It has the practical disadvantage of throwing a large part of the Mississippi Drainage-Basin into a single field, a result of chance in the frequencies over a territory of rather gentle relief. In order to mitigate this disadvantage an additional isarythm, showing the frequency of 3/16 of the days of the year, has been added. The adopted arrangement also has the disadvantage of generalizing conditions in a region of unusual geomorphological significance, the high mountainous areas of the West. The climatic records themselves permit no other course but in order to overcome this limitation slightly the isarythm of 3/8 of the days of the year has also been added to the map. The two isarythms not included in the regular fractional series are shown as dashed lines, whereas the others are solid.

Effect of elevation

Basic climatological data are least numerous in mountainous regions and climatic mapping is there least subject to accurate control. In many regards these are the most interesting areas from the viewpoint of the present study, because of their high-frequency values, and they are deserving of special consideration. Among the highest frequencies in the United States are those encountered in western Colorado, some of which are tabulated in Table 3.

Table 3--Frequency of alternations between freeze and thaw related to elevations in western Colorado

Station	Elevation	Frequency	Station	Elevation	Frequency
	ft			ft	
Leadville	10,248	165	Durango	6,550	142
Fraser	8,671	188	Meeker	6,182	149
Gunnison	7,670	149	Glenwood Springs	5,823	135
Garnett	7,576	174	Montrose	5,811	112
Steamboat Springs	6,750	143	Paonia	5,694	103
Grand Junction	4,602	80			

The relationship between elevation and frequency in alternations between freeze and thaw is striking in these western Colorado stations. If the upper five and the lower six are averaged we gain the suggestion that for the elevation 7,911 feet there should be 160 alternations per year, while at 5,622 feet there should be but 116, or, in other words, that the frequency is increased by one in each 52 feet of increase in elevation. If the frequency at Leadville is disregarded on the basis of thermometer-exposure favoring fewer alternations than are actually typical of the elevation, a comparison between Fraser and Grand Junction suggests that an increase of one alternation accompanies each 37 feet increase in elevation. (According to the "Sectional summary of climatological data," Section 7, with records ending in 1922 [p. 15], the station at Leadville is so located that "Air drainage [is] good, and conditions [are] less favorable to frost than [in the] district generally.") Between Fraser and Paonia the rate is one per 35 feet.

The higher Colorado stations experience alternations between freeze and thaw during all months of the year. Reduction in frequencies at lower elevations is chiefly the result of warmer temperatures in summer. Fraser averages six alternations during July and August, whereas Paonia always has a season of from three to four months of temperatures higher than 28°F. Some extreme-season contrasts for stations in western Colorado are shown in Table 4.

Leadville, Fraser, Gunnison, Steamboat Springs, and Meeker have all experienced effective freezes in July, whereas the lower-elevation stations farther down in the list have not. All of the stations have experienced effective thaws in January, and by wide margins. The third column of Table 4 shows that Garnett, Durango, and all stations at lower elevations experience effective thaws on the average January day. No station experiences a freeze on the average July day, but the margin at Fraser is not large. The frostless season, as reported by the Weather Bureau, varies from zero at highest elevations to about three and one-half months at the lowest station.

It might be supposed that a long season of winter freeze would reduce frequencies in alternations between effective freeze and thaw at the highest summit levels in Colorado. Temperature-

Table 4--Extreme-season climatic records in western Colorado

Station	Temperatures				Killing frost	
	Lowest in July	Highest in January	Mean maximum in January	Mean minimum in July	Latest in spring	Earliest in autumn
	°F	°F	°F	°F		
Leadville	28	52	29.1	40.6	Jul. 28	Aug. 2
Fraser	24	48	27.2	35.8	Jul. 31	Aug. 1
Gunnison	26	49	23.9	42.6	Jul. 29	Aug. 1
Garnett	29	60	35.0	44.6	Jul. 7	Aug. 13
Steamboat Springs	21	57	29.1	39.3	Jul. 30	Aug. 2
Durango	31	61	38.8	50.7	Jun. 5	Sep. 11
Meeker	26	61	35.9	45.0	Jul. 13	Aug. 22
Glenwood Springs	30	54	37.1	45.7	Jul. 4	Aug. 9
Montrose	40	62	36.2	54.4	Jun. 8	Sep. 14
Paonia	41	60	37.8	54.7	Jun. 2	Sep. 21
Grand Junction	48	62	36.2	63.7	May 27	Sep. 11

Table 5--Station-group averages with regard to frequencies of alternation between effective freeze and thaw, related to elevations, by districts

District	Average frequency of alternation between effective freeze and thaw (elevations in feet)		
	Highest	Intermediate	Lowest
W. and s. Wyoming	132 (7709)	119 (6469)	111 (5242)
N. New Mexico	136 (6921)	105 (5889)	88 (4252)
N. Arizona	133 (6758)	123 (5136)	55 (3379)
W. Utah	110 (5951)	103 (4527)	68 (4306)
Nevada	110 (5825)	116 (4459)	79 (3157)
N. and sw. Montana	99 (5343)	99 (4026)	79 (3013)
S. Idaho	97 (5263)	109 (4238)	92 (2741)
Nw. Texas	80 (3656)	43 (2228)	35 (1239)
W. Oregon	92 (3623)	28 (424)	24 (102)
E. Oregon	96 (3118)	64 (2315)	54 (1164)
N. Idaho	68 (2866)	76 (2088)	55 (1149)
E. Tenn., w. N. Car.	69 (2837)	59 (1367)	42 (865)
E. Washington	86 (2509)	70 (1718)	48 (1229)
New England	71 (709)	69 (314)	52 (91)

records are too few in number to furnish positive information, but observations from nearby levels fail to support the thesis. Leadville is not much lower than 4000 feet from the highest summits. During January and February combined it experiences an average of 31 alternations, or slightly more than one in two days. It has recorded a temperature of 52°F in January. If there is any reduction at higher elevations the effect could only occur during January and February. It is likely more than offset by higher summer-month frequencies. Other mountainous districts confirm these conclusions.

Fourteen different mountainous districts were subjected to a study of group-records. In each district the records were classified according to elevation and divided into highest, intermediate, and lowest groups, so that each group has approximately one-third of the district records. The average frequency count and the average elevation were determined for each group, with the results given in Table 5.

A more general grouping of all the stations in the Colorado Plateaus and adjacent ranges indicated 133 alternations for stations with an average elevation of 7,108 feet, 103 for 5,509 feet, 98 for 4,414 feet, and 61 for 2,706 feet. Between the highest and lowest of these groups an increase of one alternation exists for each average increase of 61 feet feet in elevation.

The general rule that increased frequency in alternations between freeze and thaw occurs at higher elevations finds an exception over a rather large district extending from western Montana through Idaho into Nevada. Intermediate elevation-groups here exhibit higher frequencies than do the higher-elevation stations. It is characteristic of this entire region that practically all freezes occur during the colder half of the year. Lower frequencies at highest elevations mean fewer mid-

winter thaws. Station-records indicate higher frequencies in March than in January. The underlying cause of this condition may be complex. In part it is probably related to air-mass distribution and in part it may be the effect of snow-cover, for maximum precipitation occurs in the winter over the entire district. Elsewhere there seem to be no clearly indicated exceptions to the general rule that alternations are more numerous at increased elevations.

Effect of the Great Lakes

Lakes Erie and Superior are each enclosed by isarythms within which fewer than 46 alternations between effective freeze and thaw occur each year. Erie, Pennsylvania, experiences 44, whereas Brooksville, less than 90 miles away from the lake, with 109, has the highest frequency noted east of the Great Plains. Frequencies for near-shore stations in Michigan include: Calumet, 44; Houghton, 47; and Sault Ste. Marie, 48. Duluth, with 54, has the lowest frequency in Minnesota. Lakes Huron and Michigan have similar effects. In Michigan, Ludington experiences 48 alternations, Alpena, 49, Escanaba, 51, and Harbor Beach, 54. Green Bay, with 52, has the lowest frequency noted for Wisconsin. Manitowoc has but 58, whereas among inland stations are such values as 90 for Hatfield and 92 for Solon Springs.

Low frequencies along the coast result from both prevention of thaw in the cold season and prevention of freeze during the warm. This may be demonstrated by the records of such pairs of lake and inland stations as Sault Ste. Marie and West Branch. The former has one of the lowest frequencies in Michigan, 48, and the latter the highest, 85. These stations are less than 160 miles apart and differ less than 300 feet in elevation. Their monthly averages are as in Table 6.

Table 6--Frequency of effective freeze and thaw, by months, for two nearby Michigan stations

Station	Sep.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May
Sault Ste. Marie	0.0	2.7	9.6	6.0	3.8	4.8	9.9	11.6	1.3
West Branch	0.7	6.7	13.6	9.9	8.7	10.8	15.8	16.6	4.1
					Percentage of annual total				
Sault Ste. Marie	0	5	18	12	8	10	24	21	2
West Branch	1	7	15	12	11	12	19	18	5

Mean temperatures are below freezing for both stations during the period December to March, the coldest month being February, with a mean of 12°F at Sault Ste. Marie and 16°F at West Branch. Mean maximum temperatures are below freezing for the same months at Sault Ste. Marie but for only three months at West Branch, where the March value is 39°F. The annual march of freeze and thaw frequencies has similar characteristics for the two stations, lower values for the four coldest months being flanked by higher values in November and April, the average months of transition between frozen and unfrozen conditions. Significant contrasts between the stations is most readily seen in terms of percentages of alternations occurring within individual months. Freezes are prevented by proximity to water to an extent where none occur in September and only 5 per cent of the annual total in October at Sault Ste. Marie, whereas West Branch has about 1 per cent of its total in September and 7 per cent in October. During the transitional month of November the coastal station records 18 per cent of its annual alternations and the inland station but 15 per cent. The higher value on the coast is the result of more frequent thawing. During December, January, and February thaw becomes a less common experience along the coast, so that alternations amount to only 30 per cent of the annual total at Sault Ste. Marie, whereas the proportion at West Branch is 35 per cent. After the transitional months of March and April the effect of open water is again evident along the coast. Sault Ste. Marie experiences only 2 per cent of its freezes and thaws in May, whereas at West Branch the percentage is five.

Effect of latitude

In tropical lowlands, where freezes never occur, the frequency of freeze and thaw must be zero. It is possible that some polar regions wholly escape thaw. In the highest tropical areas alternations between freeze and thaw occur almost daily, with thaws in afternoons and freezes each night. From this maximum-frequency zone values drop off in all directions; upward because thaws are less frequent, downward because freezes are less frequent, and poleward because seasonal contrasts of temperature become sharper.

To single out the effect of latitude alone on frequency of freeze and thaw we should confine our attentions to continental interiors, and particularly to such regions as lie far from mountains.

Table 7--Frequency of effective freeze and thaw, by months, for three inland stations in differing latitudes

Station	Approximate latitude	Sep.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Ann.
Crosby, North Dakota	49°N	1.6	9.0	13.1	7.9	4.8	6.4	14.1	10.2	3.2	0.6	71.5
Bridgeport, Nebraska	42°N	0.6	8.0	21.5	21.0	21.7	22.0	21.7	9.2	1.2	0.0	126.9
Dalhart, Texas	36°N	0.0	2.9	16.0	24.4	23.9	22.1	15.9	3.8	0.6	0.0	109.6
						Percentage of annual total						
Crosby, North Dakota		2.2	11.6	18.2	11.0	6.7	8.9	19.8	14.6	4.5	....	.....
Bridgeport, Nebraska		0.4	6.3	16.9	16.7	17.2	17.4	17.2	7.2	0.9	....	.....
Dalhart, Texas		....	2.7	14.6	22.1	21.7	20.0	14.4	3.5	0.5	....	.....

In North America zero-frequencies are characteristic of lowlands as far north as southern Florida and southernmost Texas, but in each case there is significant maritime influence. Low frequencies occur beyond the Arctic Circle. A belt of maximum frequency crosses the United States. It stands out most clearly in station-records of the semi-arid strip between Montana and Texas. Eastward it may be noted on the map of Figure 1, particularly in eastward projections of the 68- and 91-day isarythms. The characteristics of this maximum-frequency belt may be considered in discussing the monthly records of three representative stations as in Table 7.

The long winter-freeze at the North Dakota station is responsible for the annual frequency of less than 72. Fewer than five effective thaws occur each January. The annual march is characterized by a double maximum of effective freeze-and-thaw frequency and a ten-month span. An increase of 55 alternations occurs at the Nebraska station, where the winter is less severe and about as many alternations occur in January as in any other month. The double maximum of the Dakota station is reflected very weakly in values during November and February for the Nebraska station. Southerly position advances the maximum in spring by a month. The Texas station actually experiences more alternations per year than Crosby, but they are crowded into an eight-month span, with a single peak, in mid-winter. At more southerly stations the number of effective freezes drops notably and the season to which they are restricted is correspondingly shortened. At Brownsville, in southernmost Texas, only 13 alternations between effective freeze and thaw occurred in 18 years and of these 12 were in December or January, with but one in February.

The effect of latitude is somewhat less striking along coasts, where all values are lower, and maximum frequency is displaced poleward. Along the Atlantic seaboard frequencies of zero extend as far northward as St. Augustine, Florida. Values rise progressively to Eastport, Maine, with 54, and attain their maximum beyond the United States. Zero-values extend up Pacific Coast lowlands to San Francisco. Tatoosh Island, the station farthest northwest in Washington, averages but one alternation per year. It is probable that maximum frequencies between effective freeze and thaw along the Pacific Coast of North America occur in northernmost Alaska.

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A COMPARATIVE STUDY OF RAIN-GAGES

H. C. Storey and E. L. Hamilton

The rain-gage may be termed the basic instrument of the hydrologist because it should provide the means of answering his first question: How much water is there to deal with? This quantity must be known before subsequent questions relating to infiltration, stream-flow, ground-water, etc., may be answered. It is recognized, of course, that snow forms an important source of water, but this paper will deal only with precipitation in the form of rain. The conventional rain-gage consists of a sharp-edged collecting-ring--the receiver--made to an accurate diameter of eight inches, a collector-can, and a support, the assembly having a total height of about 40 inches. When it is set up, the gage is plumbed carefully so that the rim of the receiver is horizontal. Exposed in this manner a rain-gage should sample rainfall perfectly if it is set on level ground and

the rain is falling straight down. These ideal conditions are practically never realized, especially when the sampling is being carried out in mountainous regions where wind-movement is violent and changeable.

These conditions prevail on the San Dimas Experimental Forest [see 5 of "References" at end of paper] in southern California where the accurate measurement of the volume of water precipitated on the steep mountain slopes is essential to the watershed-management investigations being conducted on this area by the Forest Service. This is being accomplished by sampling rainfall through an extensive and intricate network of standard rain-gages distributed over an area of 17,000 acres. The number and the distribution of the gages were determined and checked by a statistical analysis that has been described in a previous publication [11]. This analysis showed that the method of sampling was sufficiently accurate for the end in view, providing the samples themselves were accurate.

It should be interjected at this point that none of the rain-gages on the Experimental Forest have ever been shielded. It was believed that sufficient natural protection against wind-movement would be afforded by the location of the gages in openings within the chaparral-cover of the mountain slopes.

In order to test the accuracy of the eight-inch gage in sampling rainfall at any one locality, two studies were initiated on the San Dimas Forest. The first has been completed and described in a paper entitled "An analysis of precipitation records from standard rain gages--Vertical and tilted" [10]. Here in one small watershed 22 paired eight-inch gages were installed; at each location one gage was placed vertically and the other normally to the ground-surface. Analysis of measurements from these gages showed a significant difference in that those which were tilted normally to the slope gave consistently higher readings than those exposed vertically.

The second study, which is discussed in the following pages, tested not only the eight-inch gage installed vertically but also the result of tilting the gage and lowering it near and to the ground-surface. Several other types of gages were also compared with controls and the conventional gage. The effect of shields was not considered in this study, as it was desired to study the gages per se.

Experimental procedure

Since it was essential to obtain a good measure of the actual amount of precipitation that reaches the slopes, three circular concrete surfaces were installed to serve as controls in the study. These surfaces were ten feet in diameter, laid flush with the ground-surface and parallel to the slope. Each was provided with a metal border-strip to serve as a sharp cutting edge. The surfaces were installed near the top of a small hill (see map and profile, Figs. 1 and 2), each on a different exposure, one facing east, one south, and the other northwest. The catch of each concrete surface was measured in catchment-tanks and was assumed to be a close measure of rainfall actually landing on the Earth in the immediate vicinity of the surface.

Immediately adjacent to each surface, gages were installed in the following manner (Figs. 3 and 4):

(1) Standard eight-inch gage set vertically and at the height above ground prescribed by Weather Bureau practice.

(2) Standard eight-inch gage tilted normally to the ground-surface and at conventional height. This type of exposure follows the recommendation by Pagliuca [6], though omitting the shield.

(3) Standard eight-inch gage tilted normally to the ground-surface and set in a pit so that the top of the funnel was one foot above ground. The recommendation of the British Meteorological Office was followed here with the exception that the gage was tilted normally to the ground-slope.

(4) Standard eight-inch gage tilted normally to the ground-surface and set in a pit so that the top of the funnel was flush with the ground; the adjacent ground-surface was covered with brush-cuttings to prevent splash into the gage. Here the installation was designed to combine the features of (2) and (3) to the best advantage.

(5) Standard eight-inch gage set vertically in a pit so that the top of the funnel was flush with the ground-surface; ground-surface covered with brush-cuttings to prevent splash into the gage [4,2,9]. This is the good old pit-gage that has been the subject of research by many investigators for nearly a century.

(6) Eight-inch gage of standard height equipped with a funnel that was cut on a bias so that the opening presented an ellipse in the plane of the ground-surface and an eight-inch circle on a horizontal plane. This unusual gage was designed in an effort to combine the effect of a tilt on a

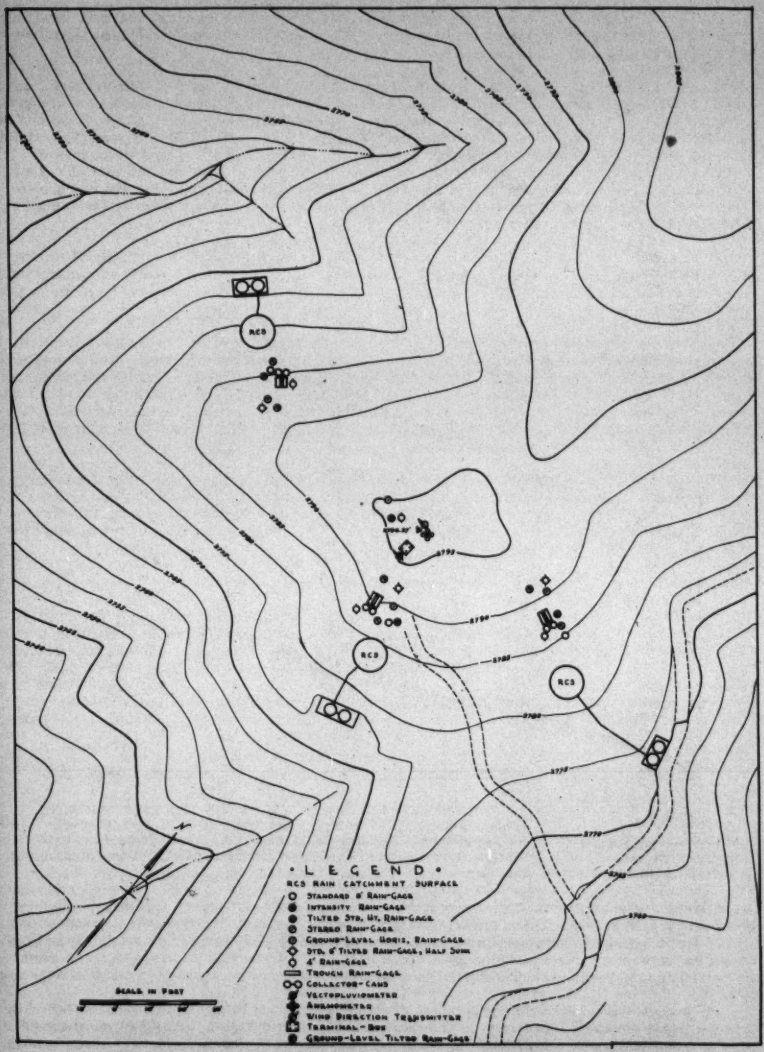

Fig. 1--Map of Rain-Gage Hill, California Forest and Range Experiment Station

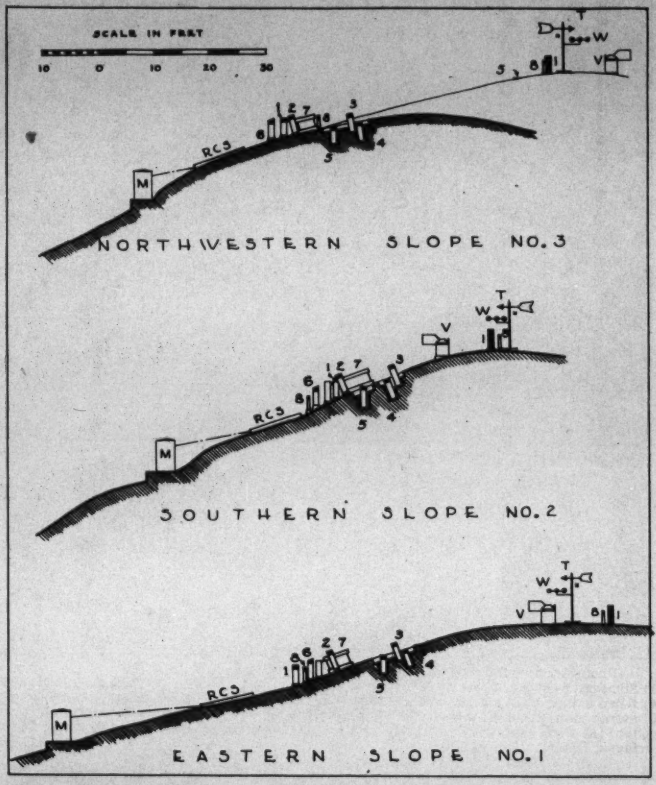

Fig. 2--Profiles, Rain-Gage Hill
(1) Standard 8-inch rain-gage; (2) tilted 8-inch rain-gage; (3) tilted 8-inch gage, half sunk; (4) tilted 8-inch gage sunk to ground-level; (5) vertical 8-inch gage sunk to ground-level; (6) stereo rain-gage; (7) trough rain-gage; (8) 4-inch rain-gage; (W) wind-direction transmitter; (A) anemometer; (I) intensity rain-gage; (V) vectopluviometer; (RCS) rain-catchment surfaces; (MM) collector-tanks

standard type of gage with its ordinary performance. It is called a "stereo rain-gage" after the design suggested by Pers [7] and further recommended by Boutaric [1]. However, the construction of the receiver has been simplified from that proposed by Pers to simple circular and elliptic forms rather than a projection of the area whose rain-catch it was designed to sample. A gage of this type has also been designed and used by Hayes in northern Idaho [3].

(7) Trough-type gage, which consists of a trough having a rectangular plane and a semi-circular cross-section. The trough is nine inches wide and is installed parallel to the slope. A sliding cover-plate makes it possible to adjust its length so as to expose a constant projectional area of 220 square inches regardless of the slope on which the gage is set. Rainfall is measured in tanks connected to the trough. So far as the authors have been able to determine, the trough-type of rain-gage was first designed by Dr. W. C. Lowdermilk and installed in 1929 at the Devil Canyon Branch of the California Forest and Range Experiment Station in southern California.

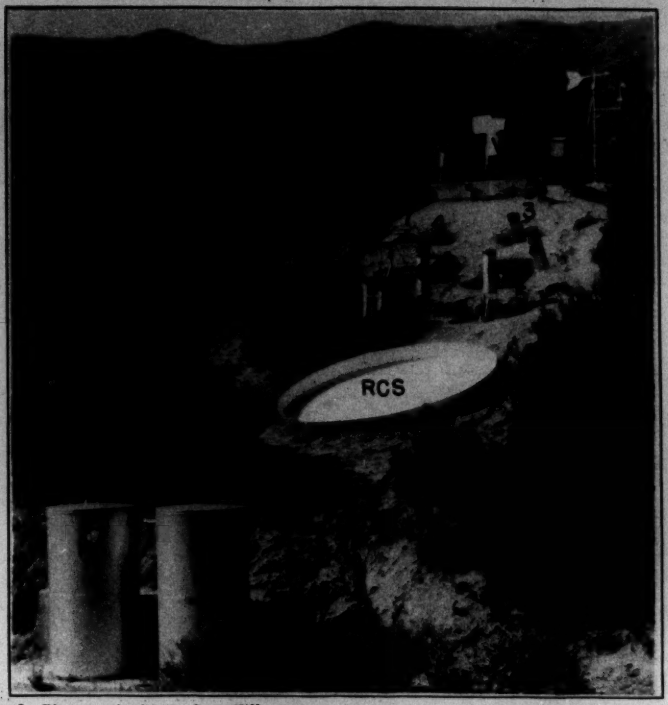

Fig. 3--Photograph of Rain-Gage Hill
(1) Standard 8-inch rain-gage; (2) tilted 8-inch rain-gage; (3) tilted 8-inch gage, half sunk; (4) tilted 8-inch gage sunk to ground-level; (5) vertical 8-inch gage sunk to ground-level; (6) stereo rain-gage; (7) trough rain-gage; (8) 4-inch rain-gage; (W) wind-direction transmitter; (A) anemometer; (I) intensity rain-gage; (V) vectopluviometer; (RCS) rain-catchment surfaces; (MM) collector-tanks

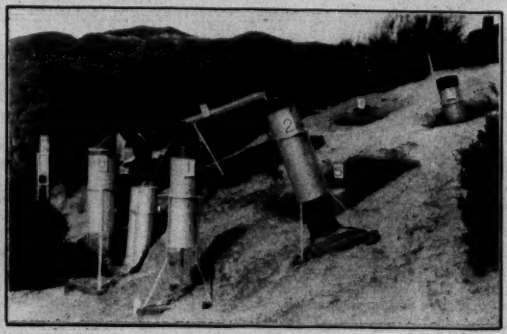

Fig. 4--Close view of gages

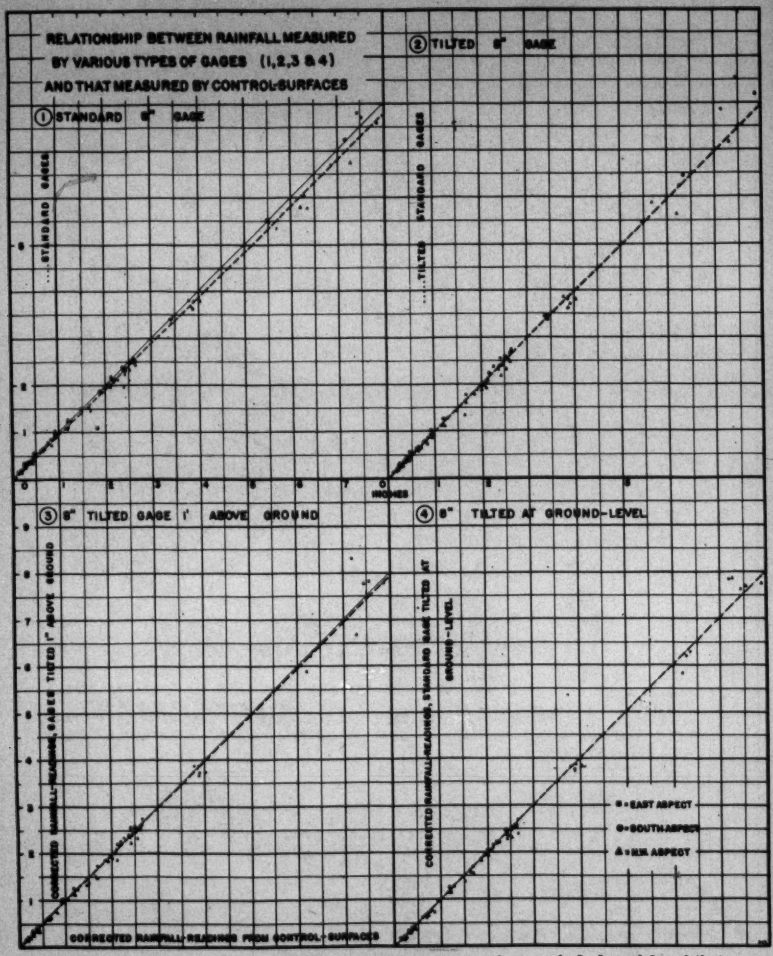
RELATIONSHIP BETWEEN RAINFALL MEASURED
BY VARIOUS TYPES OF GAGES (1,2,3 & 4)
AND THAT MEASURED BY CONTROL-SURFACES
① STANDARD 8" GAGE
② TILTED 8" GAGE
③ 8" TILTED GAGE 1' ABOVE GROUND
④ 8" TILTED AT GROUND-LEVEL
CORRECTED RAINFALL-READINGS FROM CONTROL-SURFACES
INCHES
E = EAST ASPECT
S = SOUTH ASPECT
N.W. ASPECT

Fig. 5--Relationship between rainfall measured by types of gages 1, 2, 3, and 8 and that measured by control-surfaces

(8) Four-inch gage placed vertically, its receiver the same distance above the ground as the standard eight-inch gage.

The catch of each gage and each control-surface was measured shortly after each storm. All readings for each gage and surface were converted to the equivalent readings on a horizontal plane. This placed all readings on the same basis and made the measurements applicable to horizontal areas as measured on maps.

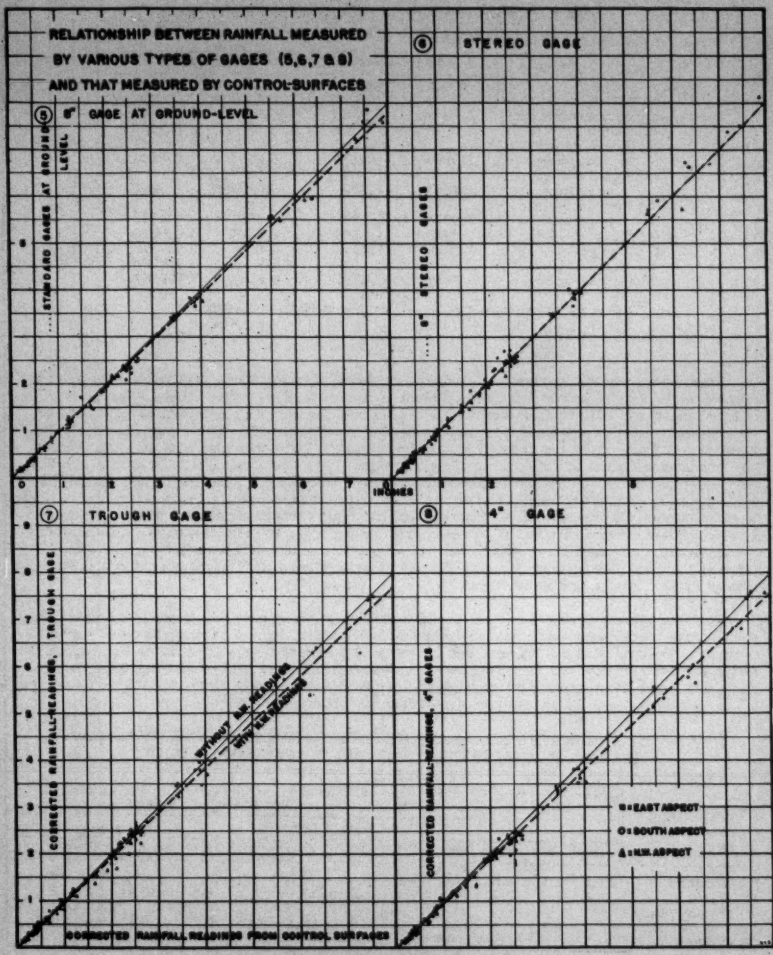

Fig. 6--Relationship between rainfall measured by types of gages 5, 6, 7, and 8 and that measured by control-surfaces

On the crest of the hill adjacent to the rain-gages and the surfaces were installed a wind-direction transmitter, an anemometer, and a tipping-bucket rain-gage, all recording. The installation also included a directional rain-gage (Fig. 3) that measured the amount of rain coming from each cardinal direction as well as the average angle at which it fell. This instrument is called a Vecto pluviometer. It was constructed, although in modified form, after an instrument designed by Robert Pers [8], a professor at the University of Grenoble in France.

Table 1--Summary of regression-coefficients for all gages plotted against concrete surfaces

Type of gage	Regression-coefficients by exposures			
	East	South	Northwest	Mean
(1) Standard 8-inch	0.9889	0.9550	0.9571	0.9704
(2) Tilted 8-inch	1.0115	1.0256	0.9644	0.9987
(3) Tilted 8-inch, 1 foot high	1.0198	1.0130	0.9457	0.9906
(4) Tilted 8-inch, at ground	1.0073	1.000	0.9799	0.9951
(5) Vertical 8-inch, at ground	0.9974	0.9704	0.9681	0.9773
(6) Stereo	1.0220	1.0226	0.9684	1.0020
(7) Trough	1.0020	1.0076	0.8911	0.9617[a] 1.0046[b]
(8) 4-inch vertical	0.9831	0.9299	0.9312	0.9481

[a]Using all three exposures. [b]Northwest exposure omitted.

Results

Since this study was designed to compare the catch of the different gages with the concrete control-surfaces, the former have been plotted as functions of the latter (Figs. 5 and 6). The line of equal catch was indicated, as well as the regression-line for the points plotted. Regression-coefficients were computed and tabulated according to exposure and type of gage (Table 1). Examination of Table 1 and the graph (Fig. 5) shows that the eight-inch standard gage has a mean regression-coefficient of 0.9704, that of the eight-inch gage placed vertically at ground level is 0.9773, while the four-inch gage is considerably lower with 0.9481. The coefficients of all the other gages are equal or slightly higher for south and east exposures and slightly lower for northwest exposures. In the case of the trough-gage, the regression-coefficient of 0.8911 appeared to be inconsistent compared with 1.0020 and 1.0076 for the other two exposures. An examination of the installation revealed that a small tree had grown so much in height as to interfere with the catch of the gage. Because of this, data for the gage have been plotted and tabulated both with and without those from the northwest exposure.

The average deviations of catches in the various types of gages from those of the concrete surfaces were computed and arranged according to exposure, type of gage, and size of storm (Table 2). Perusal of Table 2 shows that the catch of the trough-gage is consistently nearest to that of the control-surfaces, if the northwest exposure be omitted for reasons mentioned above. The other gages do not show very great deviations from the concrete surfaces with the exception of the four-inch gage. Its percentage of deviation is consistently high.

Table 2--Average deviations in per cent of various types of gages from control-surface readings, arranged by type of gage, exposure, and class of storm[a]

Type of gage	Exposure									All exposures		
	East			South			Northwest					
	Class of storm[a]											
	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
(1) Standard	4.8	2.4	2.5	10.0	5.9	6.4	12.8	7.7	4.4	9.2	5.4	4.4
(2) Tilted	6.8	2.7	2.9	10.7	4.3	2.2	15.9	3.6	4.6	10.9	4.1	3.3
(3) Tilted 8-inch, 1 foot high	6.9	3.6	4.1	11.0	4.0	2.2	15.2	9.3	5.2	10.9	5.6	3.9
(4) Tilted 8-inch, at ground	5.5	4.3	2.9	8.6	3.3	2.0	11.0	8.0	3.7	8.5	5.2	2.9
(5) Standard, at ground	6.2	2.7	2.7	9.3	3.2	4.9	12.4	6.1	3.3	9.2	4.0	3.6
(6) Stereo	10.0	4.3	4.4	10.3	4.7	3.6	12.8	5.6	3.9	10.9	4.8	4.0
(7) Trough	5.2	3.2	1.4	7.6	3.7	1.9	17.9	16.3	10.6	10.2	7.8	5.0[b]
										6.4	3.4	1.6[c]
(8) 4-inch	10.3	7.5	3.3	17.6	10.7	7.0	24.4	9.9	6.5	17.4	9.4	5.6

[a]Classes of storms: X = between 0 and 1/2 inch of rainfall; Y = between 1/2 and 1 inch of rainfall; Z = over 1 inch of rainfall. [b]Averages of all three exposures. [c]Averages of east and south exposures.

Conclusions

In the course of this study a number of interesting points have been brought out. It has been shown that rainfall-measurements made with the standard eight-inch rain-gage are consistently low. However, the accuracy of the standard gage can be increased by tilting it normal to the slope. The lowering of a gage to the ground-level will further improve its accuracy but not enough in usual practice to warrant the great amount of work required for many gages. The sunken gage is inadequate for snow measurements as pointed out by Koschnieder [4], and another obvious disadvantage is that it may be interfered with by animals. The gage partly sunk in the ground, as advocated by the British Meteorological Office, partially meets the latter two objections but is still subject to the first disadvantage as above. The stereo rain-gage gives good results but this study has shown it to be no more accurate than the standard-height tilted gage; and it is more expensive to construct. Also its aerodynamics are inferior to the tilted gage, as has been pointed out by Pagliuca [6]. Hayes, in his experiments with this type of gage, has also demonstrated its efficiency [3]. The trough rain-gage gives an excellent measure of rainfall but again its construction is somewhat intricate and fairly expensive, and, furthermore, it is unsuitable in the case of snow. However, in mountainous situations where an accurate measure of rain from a single gage is desired, the trough rain-gage is highly recommended. The four-inch gage is not recommended where it is desired to obtain reliable and consistent measurements.

Results obtained from measurements at this installation are indicative of trends but are probably conservative as to quantity. The comparison of vertical and tilted gages mentioned previously [10] indicates that more extreme differences may be obtained out in the watersheds.

The writers feel that the question of tilting the standard rain-gage is an important one. They recommend to the Committee on Rainfall of the American Geophysical Union that a new standard practice with regard to rain-gage exposure be considered wherein all gages installed for hydrologic use be exposed normally to the ground-slope at the site of the instrument.

Acknowledgment is made to the Glendora Civilian Public Service Camp No. 76 for assistance in the presentation of this paper, and especially to John A. Ohlson, of the camp, who made the statistical analysis.

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DISCUSSION

CLARENCE S. JARVIS (U. S. Engineer Corps, Washington, D. C.)--Whenever the suggestion is made that rain-gages should be set with the axis of the cylindrical vessel normal to the local country slope, the writer is convinced that whoever made the suggestion has failed to follow through to the inescapable complications and obstacles to be encountered.

First and foremost, the whole system of measurements of area depends on dimensions within a horizontal plane, and thus disregards the excess acreage actually exposed on pronounced slopes. Secondly, any attempt to define the prevailing average slope of a locality would be found ambiguous to the extent that no two observers would likely coincide in their judgments; one might be governed by the first range of hills or ridges, while the others might set their sights for the more distant crests. Thirdly, for pronounced or very steep slopes, clinometers or other instruments would be called into service in order to determine the exact degrees of slope for the record; and in order to reduce all results back to the horizontal plane reckoning, time-consuming problems in trigonometry would await solution.

It appears that for every valid reason that has been brought forward in support of tilting the rain-gages, or cutting the cylinders on the bias to fit the slope, there are several reasons of equal or greater weight that oppose such innovations. And now, to learn that the differences observed in the actual precipitation among the various gages tested, as described in the interesting paper under discussion, even including some gages set with axes of cylinders normal to the average slope in moderately rolling country, are almost negligible, or of the same order as are the inherent errors of observation and sampling, is satisfying, to say the least.

A PHOTOGRAPHIC RECORDER FOR THE DETERMINATION OF WIND-VELOCITY GRADIENTS

Leonard B. Corwin

As a part of the work connected with the development of methods for the measurement of evaporation from land- and water-surfaces, the Climatic Research Division of the Soil Conservation Service has found it necessary to make simultaneous observations of measurements of wind-velocity at several different levels. Since the observations were of necessity carried on at a distance from sources of public power, various obvious means of recording a number of simultaneous observations were not possible. No instruments for recording wind-velocity from more than two points simultaneously were available to us. After considering the possibility of adapting other recorders to produce the desired record, it was decided that photographing the dials or faces of several counters might offer the surest, and, in the end, the simplest way of obtaining the multiple records necessary.

Telephone-type counters, intended for registering the number of calls made on a circuit, were chosen, after tests on numerous types of electric counters, as satisfactory for counting the 1/60-mile contacts made by the Soil Conservation anemometers used in the gradient-measurements. The circuit to the counters required a condenser-resistor to insure obtaining one, and only one, count per contact and to prevent rapid drain of the battery when anemometers stop, as they commonly do, on contact during periods of calm.

Fourteen counters were placed at one end of a light-tight box with their dials forming a panel to which was added a clock face to give the time of observation, and four small light bulbs illuminating the appropriate symbols, N, S, E, W, to record wind-direction to eight points of the compass.

It was hoped that a standard camera could be found which would make the record desired with no more than minor alterations, and several using 16-mm or 35-mm film were tried out. Several of the 16-mm moving-picture cameras are equipped with single-frame-exposure mechanisms. One, at least, is even equipped with motor-drive and apparatus for making a series of exposures at definite but varying intervals, but, in order to obtain the type of timing required here, would have required a power-line electric clock. Of the cameras using standard 35-mm double-perforated film, some were moving-picture cameras while others were still or sequence cameras. Since a week's uninterrupted record was desired, several were eliminated because they lacked sufficient film-capacity. With exposures at 15-minute intervals, the single-frame 35-mm camera requires six feet of film per day and the double-frame camera 12 feet.

Since the requirements of the camera were simple, it was decided to build one. It consists of a light-tight box holding two 100-foot, 35-mm film-spools, a lens, with dark slide but no shutter and a film-advance sprocket which is geared to a spring-motor from an old phonograph. An electrically released pawl attached to the motor allows the film to advance one-half frame at a time. The control-mechanism consists of means of lighting a bank of lights to provide illumination to the panel of register dials and of means for advancing the film. A standard high-quality spring-driven clock is used for timing. Various timing-mechanisms were tried. The present arrangement utilizes a small electric automobile windshield-wiper motor geared to a cam-shaft which operates

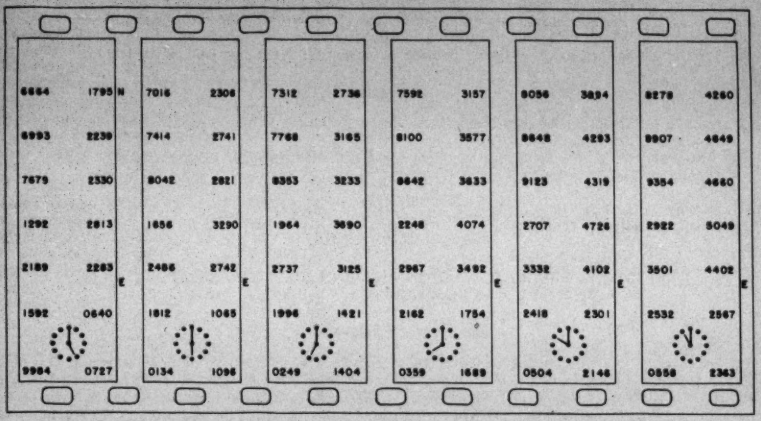

Fig. 1--Enlarged reproduction of section of film-strip for afternoon of July 25, 1942

three light, over-center switches. The first of these maintains the motor in operation after the clock-contact has reopened until a cycle is completed. The second operates the lights and the third the film-advance. This device makes it possible to control the time for each operation with great precision. For example, the exposure that was appropriate for the grade of film and the lighting circuit used was found to be approximately three seconds, and this is easily obtained.

The film, after processing, is read in an ordinary microfilm-reader whence the numerical values shown by the 14 counters and the wind-direction indications are tabulated by clock-intervals. Figure 1 is an enlarged reproduction of a section of the film-strip that contains the record for the afternoon of July 25, 1942. Only the records made on the hour are included. Tables of conversion to velocity in miles per hour have been prepared from calibrations of the anemometers and these are applied to different values obtained between clock-intervals to permit comparison of the wind-movement at various heights. These observations form the basis of two following papers [see 1 and 2 of "References" at end of paper].

In constructing this apparatus, while the immediate purpose was to obtain a continuous series of wind-gradients, thought was given to other possible uses in meteorology. By means of adjustments, photographic observations can be obtained at intervals of from one minute or less up to one hour or longer. The amount of film advanced can readily be controlled at several steps from one-quarter frame or approximately one-quarter inch up to the limit of the adjustable film-aperture, 1-1/2 frames.

To obtain photographic records of fluctuating needles or light-beams, as from a sensitive galvanometer, an exposure of less than three seconds is necessary. Since the positive-film stock in use is far less expensive than any of the faster emulsions and increased lens speed above the f 3.5 in use would be expensive, it is logical in the interest of economy to increase the illumination. A circuit giving relatively positive starting for certain of the fluorescent tubes has recently been proposed for this installation by engineers of the General Electric Company at Nela Park. This light will give a much higher actinic value per watt than the incandescent lamps in use. In terms of this recorder these lights result in a smaller battery-drain per exposure as well as shorter exposures. In addition, the tube-type lamp is most convenient for obtaining even illumination of an area such as is occupied by a small panel of instruments.

Since the mirror-galvanometer offers, by the use of thermocouples, a satisfactory means of measuring small variations in air-temperature, an attempt is being made to adapt the photographic recorder for the study of temperature-gradients.

The photographic recorder appears to offer a means of obtaining an autographic record of

many, if not most, meteorologic and climatic values. The equipment must be simplified in certain respects before it can be used as readily as a box-camera. That is our objective and it appears that further experimentation and development of the present unit may well bring it about.

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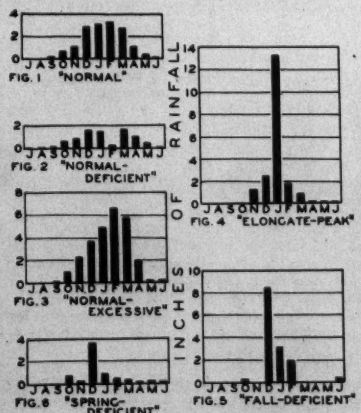
MONTHLY RAINFALL-DISTRIBUTION IN SOUTHERN CALIFORNIA, WITH SPECIAL REFERENCE TO SOIL-EROSION PROBLEMS

Maurice Donnelly

Experience in southern California in the excessively wet season of 1940-41 indicated that one step toward the reduction of erosion-losses on dry-farmed bean land would be to provide for the growth of a winter covercrop in those seasons when rainfall is above normal. This premise gave rise to the following questions: (1) What constitutes a normal rainfall-season? (2) How often may normal, abnormal, and subnormal seasons be expected? (3) Is it possible to classify the seasons according to amount and distribution of rainfall, into a few recognizable types? (4) If such a classification is possible, is there any relation between the type of season and the erosion and cropping hazard, especially on dry-farmed lima-bean lands? And (5) is there a definite sequence among the types of seasons, that is, may we expect two or three excessively wet seasons in a row?

The data most convenient for analysis of these questions are the monthly rainfall-records of the Weather Bureau at such stations as Los Angeles. These monthly records give no specific information, however, on intensity of precipitation, a factor known to be of great importance in soil-erosion. Nevertheless, these monthly records are widely available, are already tabulated for previous years, may easily be maintained for current seasons, and are, for these reasons, to be recommended for at least the preliminary analysis. Accordingly, I undertook the analysis, using the record for Los Angeles, which dates from 1877.



Figs. 1-6--The six types of rainfall-seasons

Six types of rainfall-seasons, according to monthly distribution and amount--The mean rainfall-distribution for Los Angeles for the period 1877-1942 is shown as a histogram in Figure 1. Data for this curve were obtained by adding the amounts of rain reported for each month in the years from 1877 to 1942, inclusive, and dividing by the total number of rainfall-years, namely, 65. The figure obtained in this way for each month is the mean or average rainfall for that month. For convenience, this histogram of the average or mean monthly rainfall-distribution is called the normal rainfall-curve. Note that it is not symmetrical, but is skewed slightly to the right. For Los Angeles, the mean or average rainfall for an entire year, based on the 65 years of record, is 15.5 inches. The rainfall-year, as commonly accepted in the hydrology of California, runs from July 1 to June 30.

Known also as the "Mediterranean" type and the "subtropical" type, the rainfall-curve for Los Angeles, as graphed in Figure 1, is an example of the "Pacific" type of rainfall, in which the bulk of the rain comes during the coldest part of the year.

When rainfall is graphed by months, six types of seasons may be recognized.

(1) Normal season--In a normal season, the total amount of rainfall for the year ranges from 61 to 139 per cent of the mean, that is, from 9.5 to 21.5 inches, and the distribution by months is similar to or approaches that of the normal curve shown in Figure 1.

(2) Normal-deficient season--In a normal-deficient season, the monthly rainfall-distribution is somewhat similar to the normal curve, except that January and February are notably deficient. The total amount for a normal-deficient season is less than 61 per cent of the mean, that is, less than 9.5 inches. Figure 2 shows the normal-deficient histogram derived by averaging the eight seasons classed as normal-deficient.

(3) Normal-excessive season--In a normal-excessive season, the monthly rainfall-distribution is similar to or approaches the normal curve, but the total amount for the season is greater than 139 per cent of the mean, that is, greater than 21.5 inches. Figure 3 shows the normal-excessive histogram derived by averaging the seven seasons classed as normal-excessive.

(4) Elongate-peak season--In an elongate-peak season, more rain falls in a single month than in all the rest of the months in the particular rainfall-year combined. The rainfall-distribution for 1915-16, shown in Figure 4, is an example of this type.

(5) Fall-deficient season--In the fall-deficient season, rainfall is notably deficient in the fall of the year. When rain does begin in such a year, it is usually with a heavy downpour late in December or early in January. Figure 5, showing such a fall-deficient season, is the histogram for 1933-34.

(6) Spring-deficient season--This term designates a season in which the rainfall is notably deficient in February, March, and April. Figure 6, which shows such a distribution, is the histogram for 1893-94, one of the few examples of this type.

Frequency and distribution of the six types of rainfall-season--The frequency of the six types, by number and percentage, are given below:

Type of season	Number	Percentage
Normal	30	46.1
Normal-deficient	9	13.8
Normal-excessive	7	10.8
Elongate-peak	10	15.4
Fall-deficient	7	10.8
Spring-deficient	2	3.1
Totals	65	100.0

Figure 7 shows by histograms the years of occurrence and seasonal totals of the respective types.

Frequency-distribution of total seasonal rainfall-values--It is desirable to inquire into the frequency-distribution of total seasonal rainfall-values based on class ranges of four inches. Stated in a different way, we wish to know how many seasons had total rainfall in the range from 5.5 to 9.5 inches, and so on. (In order that the class-intervals may be ranged evenly about the mean value, which is 15.5 inches, 5.5 inches is taken as the starting point rather than 5 inches.) The frequency-distribution of the seasons according to a class-interval of four inches, beginning with the interval 5.5 to 9.5 inches, is shown in Figure 8.

Since the mean rainfall at Los Angeles is 15.5 inches, it would be a natural and logical conclusion that a normal season is one in which the total rainfall is in the range, say from 14.5 to 16.5 inches; but these seasons are, as a matter of fact, rare. For the 65 years of record, only five seasons, or about eight per cent of the total, are in the range from 14.5 to 16.5 inches. If the limits of the class-interval are set at 14 and 16 inches, the proportion is even lower. Only three seasons out of the total of 65 had rainfall in the class-interval of 14 to 16 inches.

Figure 9 shows the distribution of seasonal values plotted in ascending order. As seen in the Figure, the median value (of which an equal number of occurrences are higher and lower) is 13.9 inches and the mean value is 15.5 inches.

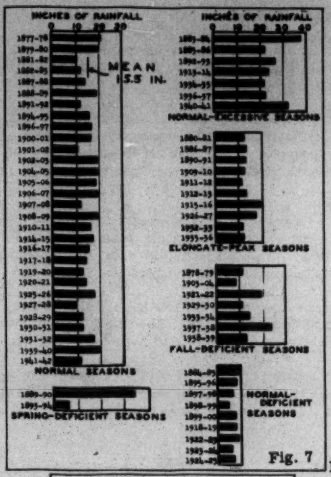


Fig. 7

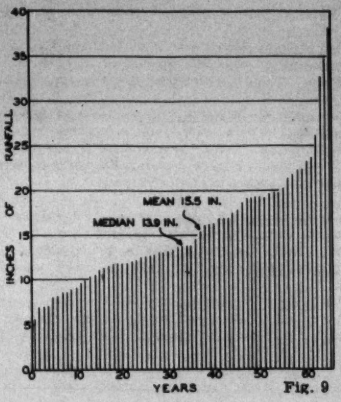


Fig. 9

Fig. 7--Years of occurrence and seasonal totals of six types of seasons

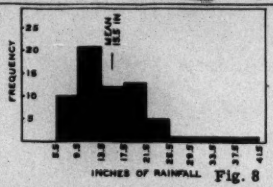


Fig. 8

Fig. 8--Frequency-distribution, seasonal rainfall-values, Los Angeles, 1877-1942 (4-inch class-intervals)

Fig. 9--Seasonal rainfall-values, Los Angeles, 1877-1942 (plotted in ascending series)

Frequency-distribution of seasonal values in relation to runoff and flood-hazard--Considering chiefly now the frequency-distribution by annual totals, some generalizations on the degree of runoff and on the flood-hazard seem legitimate.

It will be seen in Figure 8 that five class-intervals of four inches each, beginning with 5.5 inches and ending with 25.5 inches, include over 93 per cent of the total number of years. Ten seasons, or roughly one season in six, are in the class from 5.5 to 9.5 inches. These are the drought-years (see Fig. 7), of which 1923-24 (total 6.7 inches) and 1924-25 (total 7.9 inches) are examples. Little or no water runs off the land in such dry years, and floods are almost entirely absent.

Seasons classed in the interval from 9.5 to 13.5 inches are most numerous, there being 21 of them in a total of 65 or about one season in three (see Fig. 8). Depending on the seasonal type, runoff in these years may be reduced to the vanishing point by present conservation-methods (principally deep-contour subsoiling), as in 1941-42, or it may be intense and destructive to the surface-soil, despite contour subsoiling, as in 1938-39. Floods are rare in seasons of this class and when they occur, they are usually localized and caused by an especially intense and long-continued downpour over a small area.

Twelve seasons come in the class from 13.5 to 17.5 inches, and 13 in the class from 17.5 to 21.5 inches. Together they make up more than one-third of the total. Runoff is an important factor in both classes; these are the years when underground storage in southern California is replenished to a large extent. Widespread and destructive floods have occurred in seasons of these two classes; such floods appear to be closely associated with the elongate-peak type of season (1915-16 and 1926-27) and the fall-deficient type (1933-34). In a normal type of distribution, floods in seasons of these two classes do not appear to have been frequent or destructive.

Finally, five seasons fall in the class from 21.5 to 25.5 inches, and four are included in the record from 1877-1942 in which the total rainfall exceeded 25.5 inches. Runoff is high. Although the two classes include the season of the most damaging flood of record (1937-38, when the rain amounted to 23.4 inches), there is no immediate relation between high total rainfall and the flood-incidence. Thus in 1940-41, the third wettest season of the record, when over 32 inches of rain fell, most of it in February and March, floods were of low magnitude and were localized in areas where much land was bared in winter fallow. In eight out of the nine seasons when the total rainfall exceeded 21.5 inches, sizable rains fell in October or November, or both. Furthermore, seven of these eight seasons had monthly rainfall-distributions whose curves are similar to or approach that of the normal in shape. Thus, in the majority of excessively wet years, rain-distribution favored the germination and development of a protective winter covercrop. The two seasons with totals above 21.5 inches that do not conform to the normal in monthly distribution are 1889-90, classed as spring-deficient, and the flood-year, 1937-38, classed as fall-deficient.

Relation of season-type to the soil-erosion hazard on winter-fallowed land--(1) In normal-deficient seasons, the erosion-hazard on winter-fallowed land is slight. In such years the rains are scattered over several months and seldom reach an intensity high enough to produce concentrated runoff. These are the EROSIONLESS YEARS.

(2) In normal seasons, the erosion-hazard on winter-fallowed land ranges from low to severe, depending upon the total amount of rain and on individual storm-intensities. We may recognize three subtypes, based on the total amount of precipitation: (1) From 9.5 to 13.5 inches; (2) from 13.5 to 17.5 inches; and (3) from 17.5 to 21.5 inches. In the normal subtype having a seasonal value in the range 9.5 to 13.5 inches, the erosion-hazard on winter-fallowed land is low or moderately low; 1941-42 was such a season. In the normal subtype having a seasonal value in the range 13.5 to 17.5 inches, erosion on winter-fallowed land is likely to be moderately severe; the year 1931-32, with a total of 16.9 inches, was such a season. In the subtype with a seasonal value in the range from 17.5 to 21.5 inches, erosion is apt to be severe on winter-fallowed land.

The moderate or severe erosion that attacks winter-fallowed land in normal years when the total rain is in the range from 13.5 to 21.5 inches contrasts strongly with the limited erosion that takes place on seeded grain-fields in these same seasons. This comes about from the fact that the rainfall-distribution in the years classed as "normal" is such that the grain is germinated by, and has made enough growth from, early rains, that later heavier rains are prevented from doing damage. The nature of this prevention is many fold and has been discussed by numerous writers.

(3) In normal-excessive seasons, it is usually difficult to maintain winter-fallowing. Where soils persist throughout a normal-excessive season in a bare condition, it usually indicates that winter-fallowing has been carried on so persistently that seeds are scanty or absent in the upper soil, or that the operator has been able to cultivate late enough in the season to kill an incipient covercrop and inhibit a second germination. The season of 1940-41 is a good example of the relation of normal-excessive years to soil-erosion on winter-fallowed land. A sizable rain in October 1940 germinated a heavy cover on most winter-fallowed land where seeds existed. Except where this cover was killed by cultivation in late November and December, it waxed heavy and rank, benefited by warm air-temperatures in November and December, and by warm rains of December and succeeding months. By the time of peak-precipitation in February and March 1941, the winter covercrop had reached such a heavy stage of growth that it exerted a marked effect in enhancing infiltration and in retarding runoff from the long-continued gentle rains of these months. On numerous fields, however, in south coastal California, this winter covercrop was absent or feeble; on these lands soil-erosion was so severe that many parcels went out of cultivation, for our time at least, as a result of the washing that rilled and gullied them in 1940-41.

(4) The elongate-peak seasons are important in soil-erosion, because they are the seasons when barrancas (a term used in California for an alluvial-valley gully) are often cut in valleys where none existed previously in historic time. The years 1915-16 and 1926-27 are examples of elongate-peak years when barrancas were carved in many valleys which up to that time bore no definite stream-channel. Elongate-peak seasons bear such a close relation to the development and enlargement of barrancas that I propose to call them the BARRANCA YEARS. If the elongate peak is usually steep, as in 1915-16, or if pre-peak months had only limited rainfall, as in 1932-33, sheet-erosion is also likely to be severe.

(5) In fall-deficient seasons, banging rains ordinarily begin late in December or early in January. There is not time for the germination and growth of a protective plant-cover. Sheet-erosion is apt to be severe in the fall-deficient years. This type of season is represented by the season of 1933-34 (the year of the Montrose, California, sheet-flood) and 1938-39, when sheet-

erosion laid a heavy toll on all bare land in southern California. These are the years, too, when sheet-erosion is high in orchards where a covercrop has not been germinated earlier in the season by irrigation. Severe and widespread sheet-erosion on bare farm-land, and sheet-flooding on burned or overgrazed range and chaparral-land, are so closely correlated to fall-deficient seasons that I propose to call them the SHEET-EROSION YEARS.

(6) Spring-deficient seasons are of very infrequent occurrence and appear to be seasons when erosion is neither extensive nor severe.

Erosional contrasts in the 1920's and 1930's--The remarkable contrast in soil-erosion in southern California between the 1920's and 1930's helps to explain the slowness with which the erosion-problem has been recognized in the State.

In southern California in the 1920's, not only was rainfall well below the mean in total amount, but it fell, in general, in a manner favorable to soil-stabilization. Only one sheet-erosion year occurred, 1921-22. The single barranca year, 1926-27, did see a tremendous amount of channel-erosion, but such damage was probably regarded at that time as unrelated to soil conditions. In striking contrast to the 1920's, is the high level of soil-erosion in southern California in the 1930's. Of the years of the latter decade, four were sheet-erosion years, two were barranca years, and two were normal-excessive years; in only one year, 1930-31, was the rainfall favorable to soil-stabilization with respect to distribution and seasonal totals.

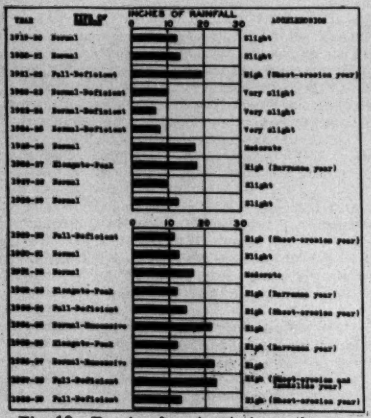


Fig. 10--Erosional contrasts in southern California in the 1920's and 1930's

Figure 10 shows graphically the erosional contrasts between the 1920's and 1930's. The term "accelerosion" [see Maurice Donnelly, Trans. Amer. Geophys. Union, p. 261, 1941], used in Figure 10, covers not only the removal of soil by surface-runoff, but also landslide-erosion induced in part by human action and accelerated-channel (barranca) erosion.

Possible prediction of erosion and flood-hazard--By use of the analysis given in this paper it may be possible to predict the erosion and flood-hazard in southern California with a fair degree of accuracy in some seasons.

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A PROGRAM IN CLIMATOLOGY

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The field of climatology has passed in the last decade, especially in the United States, through a period of relative sterility. Few if any advances have been made, and it seems appropriate to investigate into the reasons for this state of affairs and to see what remedies might be applied for improving this situation in the future. At the outset it might perhaps be appropriate to ask and answer the question if there is presently a need for climatological work, and if climatology has a future.

The current needs for climatological work during these days of war are evident to any one who reads the newspapers, and it is a fact that climatological data and analysis are as much needed in military strategy as are topographical maps, inventories of natural resources, and industrial capacity. It is no secret that there exists at the present time in conjunction with war-work a lack of well-trained climatologists who can not only compile climatic data, but who can

interpret them for all kinds of military purposes. Looking beyond the immediate need, there remains a vast field of scientific endeavor that will need fertile minds to consider questions that concern the post-war world and the time of reconstruction. There are innumerable questions involved in the applications of climatology to agriculture, world-wide airline operations, resettlement of populations, and engineering. In all of these applied fields a considerable amount of fundamental research needs to be done which at present is handled with a great deal of dilettantism.

One of the main reasons why climatology, after a great classical period at the beginning of this century, has become a field of ephemeral compilations has been the lack of appropriate facilities in the universities, and the unsatisfactory training of many persons who now claim to be climatologists. During the classical period of climatology, when Hann was its main exponent, the essential training of a climatologist tended toward a knowledge of the fundamental quantities that make up a climate--that is, a fundamental knowledge of the phenomena of weather. Yet coexistent with the meteorological approach to climatology, and still dominating the picture, is the geographical approach in training and research. For the geographer the purpose of climatological work was largely the indexing of meteorological conditions at various places which would permit regional analysis on the basis of a climatic classification. There is probably agreement among the meteorologically schooled climatologists who have worked on the classification-problem that a climatic classification per se which condenses a long period of meteorological observations into one index and simultaneously describes all climatic conditions adequately and completely is not possible. Usually classifications of climates are originally devised and intended to serve a specific purpose, such as the illustration of influence of climate on plant-cover of the Earth. It is, however, unjustified to forget these specific purposes and use, as has been done in text-books, one or the other specific climatic classification as universally descriptive of regional climates.

At any rate the problem of climatic classification should not overshadow the more important tasks in climatology, and it should be emphasized that in order to be useful a climatic classification should be devoted to a specific purpose. And it should also be remembered that a classification intended for one purpose cannot be applied to others. Therefore, while conceivably a good climatic classification for the growth of a given crop-plant can be devised, there is no reason to believe that the same classification would indicate whether one might run wind-power stations throughout the year or determine where a flight-route between two places with least interference of weather should be located. Each purpose has its own set of limiting conditions, and these limiting conditions determine the classification. The purely geographical approach to climatology, which has not led to a deeper understanding of climate, I believe will have to give way in the future to the meteorological approach which evolves climate as an outgrowth of the physical atmospheric processes. This new-style climatology, which has been postulated by other writers for some time, will have to produce a dynamic and energetic climatology which is not only tied to data observed near the surface of the Earth, but which is just as three-dimensional as modern meteorological analysis. Such an approach will, for one thing, necessitate that climatology is not just a side-line to be taken up now and then by some one who feels that he needs some climatic data in his own field, but that a school of professional climatologists should work on climatic problems. This does not mean that research on the border-line between climatology on one side and medicine, biology, and agriculture, on the other side, should be abandoned, but rather that the advances in these fields ought to be made either by persons who are well trained in both fields or else by teams composed of scientists from each field. Any one looking at recent books which have been written on the fringes of the science of climatology will be amazed at the lack of critical analysis that is prevalent in them, and which is often due to the fact that climatic data have been misinterpreted. Also, whoever in the last ten or fifteen years has taken a look into climatological master's theses and doctoral dissertations as they have appeared in the two countries where perhaps most work along the line of climatology was done, namely, the United States and Germany, must feel rather appalled by the idea that degrees have been given on the basis of studies which are nothing but compilations of data and which are so stereotyped that it is hard to see how any one could classify them as original research. In a large number of cases a clerk given the scheme of such a dissertation and armed with a calculating machine could have done just about the same.

One additional reason why at this present moment the necessity of meteorologically trained climatologists becomes very obvious is the fact that the mother-field of meteorology itself has to make further use of climatic data for its own purposes, especially in the field of long-range forecasting.

The first step that is to be taken to remedy the situation is clearly indicated. It is the establishment of appropriate teaching facilities for climatology. From what is known at present about the situation of universities in Continental Europe which took some interest in this field of work

and which had chairs or professorships in climatology, it may well be said that they have either completely vanished or have been reduced to such a state that no fundamental advances can be expected for years to come. In the United States, since the death of Professor Ward at Harvard, I believe, there has not been a full-time academic full professorship devoted exclusively to the field of climatology at any university. In line with the future applications of climatology for practical purposes there would seem to be a need of not only one but perhaps three institutions which should have climatological professorships. One should be devoted to the interrelations between climatology and meteorology and other fields of geophysics, and therefore be in conjunction with one of the professional meteorological schools in the country. A second one should have as a main trend of work the biological applications of climatology, and probably would be most profitably located in conjunction with a school of agriculture. The third one should apply climatology to the questions of anthropology and health, and should therefore be closely related to a medical school which devotes considerable attention to anthropology, epidemiology, and questions of public health.

The second point in a climatological renaissance should be the reexamination of the established practices in the central meteorological offices of various countries. It seems that the period of accumulation of data in many countries ought to be replaced, or at least balanced, by a period of analysis of data. In each meteorological library one can find shelves after shelves and files on files with climatic data accumulated day by day which never have been subjected to anything but the most elementary adding and averaging processes. In some cases it is very doubtful if further accumulation of similar data for a period of an additional 50 or 100 years would give us any more information on the climate of a place than we already have. On the other hand, it has not even been satisfactorily established whether or not the data that are now being recorded are the ones that are of greatest importance, or of the greatest analytical value. It might conceivably be that instead of having 20 stations recording the temperature in some area, it would be of greater advantage to have one station recording the intensity of solar radiation. This should not be interpreted to mean that micro-climatic networks which have been established are to be abandoned. As a matter of fact, such networks should be strengthened and multiplied if the purpose on hand warrants it. Flood-investigations, investigations on fruit frosts, and similar things might actually need a greatly reinforced network of stations unless analytical methods will prove that a greater density of observations will not yield any further refinement of the results.

The first two necessary developments, training and reorientation of central climatic services, should go hand in hand in the sense that professionally trained climatologists will be available for such central agencies as the United States Weather Bureau, and help in revising such procedures as may have become obsolete and introduce such renovations as a vigorous university research-program may produce. It is realized here that in the past official agencies such as the Weather Bureau have had to struggle continuously for funds, and it is therefore readily to be understood that some of their activities have not been modernized to the extent that other activities have been. It is an essential function of people outside of Government agencies to see to it that these agencies will get the funds that they will need in order to render professionally satisfactory services.

A third point of the program concerns a necessary tool for the renaissance of climatology, and that is an appropriate place for the publication of climatological papers and monographs of a fundamental nature. The meteorological journals of the various countries have often been reluctant to accept climatic papers, and I do not refer only to the compilations, but even papers of considerable importance, because they are usually voluminous. In recent years longer climatic papers have been published, if at all, by central Government institutions. The circulation of such material is haphazard, and for those outside of Government agencies there is no means to convey their ideas to other colleagues in the field. If, as we hope, a progressive and rejuvenated science of climatology with innumerable practical applications shall become a reality, an independent journal under professional editorship seems indispensable.

It is not the intention of this paper to cover in all detail what research-projects might advantageously be undertaken, nor to outline what the training of a professional climatologist should be, nor to make proposals for the reorganization of the work of Government agencies. Such details can better be presented to a smaller group of interested persons so that they may be subjected to criticism and discussion.

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SOIL-TEMPERATURE IN THE MATANUSKA VALLEY OF ALASKA: OBSERVATIONS OF 1941

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The observations upon which this paper is based were made by a General Land Office land-classification field-party in the Matanuska Lowland of Alaska between July 3 and September 10, 1941. They include observations widely scattered in time and space taken with pocket thermometers in the walls of shallow holes dug for the purpose, and records obtained by a three-element soil-thermograph, which we installed on July 12 at the Experiment Station near Matanuska. The six-inch pocket thermometers used were of two types, the Taylor Binoc, a mercurial thermometer with one-degree graduations from -30° to +120°F, and the Taylor Permacolor, an alcohol thermometer with two-degree graduations from -20° to +120°F.

One series of pocket-thermometer observations was taken to provide a comparison of soil-temperatures in open fields with those under forest-cover. The other pocket-thermometer observations were taken in connection with other activities that determined the movements of the party rather than at times and places specifically chosen for the purpose. Their distribution was, however, sufficiently wide to test most situations.

The thermograph, manufactured by the Brown Instrument Company, Philadelphia, had three lead-sheathed sensitive elements connected to the recording apparatus with flexible cables about eight feet long. The three pens were designed to trace a continuous record on a circular sheet 12

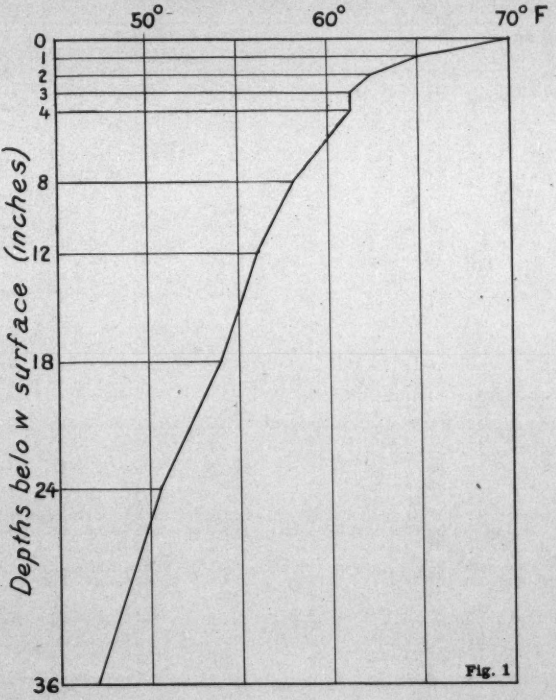

Fig. 1

Table 1--Soil-temperatures observed with pocket thermometers

Number of readings	No. of observations at			
	Surface	2 inches	4 inches	8 inches
Over 90	2	...	...	...
80 - 89	1	...	...	...
70 - 79	5	3	2	...
60 - 69	9	9	12	7
50 - 59	8	5	19	23
40 - 49	...	2	5	9
30 - 39	...	...	...	2
Totals	25	19	38	41
	°F	°F	°F	°F
(1) Absolute maximum	97	76	70.5	66
(2) Absolute minimum	50.5	46	42	36.5
(3) Absolute minimum (not over frost)	50.5	50	48	45.5
Absolute range [(1) - (3)]	46.5	26	22.5	20.5

Table 2--Observations summarized in Table 1

(The first observations were taken to depths of 30 to 36 inches, with few values for 2 inches or surface-temperatures; later the practice was to take more readings near the surface and fewer below 8 inches)

Date	Time	Temperatures at			
		Surface	2 inches	4 inches	8 inches
	h m	°F	°F	°F	°F
July 3	11 45 a.m.	.....	62.5	61	58
	01 15 p.m.	.....	.....	54.5	52
	01 20 p.m.	.....	.....	49.5	46
4	03 30 p.m.	.....	.....	58	55
5	10 40 a.m.	66	.....	60.5	57
	12 00 m	60	.....	53	50
6	10 00 a.m.	.....	56	48	46
	12 32 p.m.	62	.....	55	53
	01 30 p.m.	.....	.....	63	58
	01 55 p.m.	.....	.....	52	49.5
	.. ..	.....	.....	61	59
7	10 00 a.m.	.....	.....	57	56
	10 30 a.m.	.....	.....	50	49.5
	02 35 p.m.	.....	.....	63	58
8	08 50 a.m.	62	.....	57.5	56
	09 20 a.m.	54	.....	51	48.5
9	09 10 a.m.	58	.....	56	55.5
10	09 55 a.m.	53	.....	50	49
	10 10 a.m.	.....	.....	49.5	47.5
	10 50 a.m.	60.5	.....	55.5	53.5
11	04 35 p.m.	89	76	70.5	64
12	11 05 a.m.	97	69.5	63	60.5
16	05 00 p.m.	68	68	66	63
18	11 45 a.m.	56	.....	54	54.5
	12 05 p.m.	50.5	.....	50	49.5
	04 00 p.m.	57	56.5	57	56
21	09 30 a.m.	90	68	62.5	61
26	03 30 p.m.	.....	50	49	45.5
27	01 35 p.m.	76	65.5	59	57
	02 10 p.m.	59.5	57	52	50
29	07 00 p.m.	.....	46	42	36.5
Aug. 4	03 00 p.m.	74	72	68	62
	03 30 p.m.	71	67.5	65	58.5
	05 08 p.m.	58	46	44	39
6	04 00 p.m.	68	67	64	59
	05 00 p.m.	66	67+	66	62
11	05 25 p.m.	78	74+	70.5	66
15	11 40 a.m.	73	60	56.5	54
30	02 30 p.m.	60	58	55	50

Table 3--Comparative temperatures under a crop of oats-peas (Station A) and under birch-spruce forest (Station B)

Station	Time	Air temperature	Depth in inches				
			Surface	4	8	12	18
	h m	°F	°F	°F	°F	°F	°F
A	09 30 a.m.	67	68	59	57.5	56	54
	10 30 a.m.	70	68	59	57.5	56	54
	11 30 a.m.	70	76	59	57	55.5	54
	02 30 p.m.	72	79	62	58	56	54
	03 30 p.m.	74	76	62	58	56	54
	04 30 p.m.	67	70	63	58.5	56	54
	05 30 p.m.	57.5	67	62	57	56	54
B	10 00 a.m.	64.5	54	52	50	49	47.5
	11 00 a.m.	68	62	52	50	48	48
	12 00 a.m.	69	62	57	52.5	52	50
	02 00 p.m.	72	69.5	58	54	52	50
	03 00 p.m.	73	69	56	54	53	50
	04 00 p.m.	68	64	58	55	52	50
	05 00 p.m.	65	63.5	58	54	53	50

inches in diameter covering a period of a full week. The instrument was adjusted at weekly intervals or oftener by testing with the pocket thermometers close to the place where the sensitive elements were buried. The three sensitive elements were buried at, respectively, 2, 4, and 8 inches below the surface of a plot bare of vegetation, on the experiment-station grounds near Matanuska Village. The site was on a nearly flat surface a quarter of a mile wide and about a mile long. The nearest forest-cover was at least two hundred yards distant.

The choice of depths for the three thermograph-records was governed by early observations with pocket thermometers, which indicated that below eight inches the diurnal fluctuation of temperature was inconsiderable, and evidence that the temperatures significant for plant-growth were those near the surface. The vertical temperature-profile shown in Figure 1 illustrates the rapid change with depth in the surface-layers near midday, and the slower, steady decline below three inches. Most plants in Alaska are shallow-rooted, many of the crop-plants being more shallow-rooted than is their habit in the United States.

It was planned to have the soil-thermograph installed under a crop cover during the summer of 1942 at the Experiment Station at Matanuska, but a shortage of manpower at the Station made this impossible of accomplishment. It is now planned to ship the soil-thermograph to Fairbanks and install the instrument in the vicinity of that city to obtain records through a comparable season.

Air-temperatures were taken in some instances with the Taylor pocket thermometers, but in most cases with a manually aspirated psychrometer, Friez H.A. 2, with a pair of matched six-inch thermometers graduated to 1°F and reading from +10° to +110°.

Soil-temperatures at several depths at all times of day and spread over the months of July and August (Tables 1 and 2) show a relatively narrow absolute range decreasing with depth except for some observations over permafrost.

Table 3, comparative temperatures under (a) young oat-pea crop and (b) birch-spruce forest, shows cultivated land warmer by 8°.5 or more at all depths even on a cloudy day.

The surface-temperatures were taken in the top half-inch, just deep enough to avoid disturbing the soil-particles above the thermometer-bulb. Where there was no vegetation-cover the passage of light clouds in front of the Sun caused an immediate fall of 2° to 3° in the temperature of this surface-layer. At the other extreme, under a moss-cover, even the top layers of soil reacted very little to changes in sunshine or air-temperature. Temperature-inversions in the upper layers occurred on most clear nights under a bare surface but not under a vegetative cover.

At eight inches below the surface the diurnal variation as recorded by the soil-thermograph was on the order of 3°F in clear weather and less than 1°F in rainy or cloudy weather. At four inches the diurnal range was on the order of 15°F in clear weather and 8°F in cloudy weather. At two inches the diurnal range was of the order of 25°F in clear weather and 8°F in cloudy weather. Minimum temperatures at two inches were commonly 12°F to 14°F lower than minima at eight inches.

U. S. Board on Geographical Names,
Washington, D. C.

THE MICROCLIMATES OF A SMALL VALLEY IN CENTRAL OHIO

John N. Wolfe, Richard T. Wareham, and Herbert T. Scofield

Introduction
Edgar N. Transeau

The richness of the floras of deep valleys having youthful topography has often been remarked. The diversity of the smaller plant communities that live on cliff-tops, rock-surfaces, talus slopes, and stream-margins, and the complicated patterns they form on the valley-surfaces have been frequently described. Usually these plant mosaics have been interpreted on the basis of available water-supplies, and the physical and chemical variations in the local substrate. Great as are these diversities within a mile-long valley, there is good reason to believe that the atmospheric and above-ground factors are equally diversified and equally important in any adequate delineation of the conditions in which many small communities of plants live.

Moreover, these microenvironments are not static, but are continually increasing or decreasing in area, and are undergoing progressive modification of the site-factors that promote the growth of one plant species and retard the growth of another.

It is not improbable that the microclimatic factors have more to do with these dynamic interrelations of the community mosaic than have the substrate factors. Certainly they are the master factors in the cyclic seasonal periodicity of individual plants and plant-communities, such as the period of germination, growth, reproduction, dormancy, or death. They are, also, effective agents in the gradual modification of the substrates and the microenvironments which are the forerunners of changes in the vegetation-patterns of the valley.

Almost four years ago three of my associates undertook, with the aid of a battery of several hundred recording instruments, the arduous task of studying such a valley located about 50 miles southeast of Columbus, Ohio. They have had to develop new instruments, new installations, and new methods of procedure to carry out their program. They have visited the area on every week-end since that time, have serviced the instruments and recorded the plant phenomena, along with the meteorological data, and have a series of photographs to substantiate some of the changes that have taken place during this period.

During some weeks one or more of the group have spent several successive days in the valley, making observations of the hourly fluctuations in temperature, light-intensities, and humidity-changes in various parts of the valley. They have now accumulated enough data to begin an analysis of the atmospheric conditions and the seasonal variations in relation to plant growth and distribution. The following paper summarizes certain phases of the work.

The valley chosen for the study is located at the western edge of the Allegheny Plateau in central Ohio. Here the Black Hand formation contains massive layers of resistant sandstone and shale. When the continental glaciers invaded central Ohio, the 200- to 400-foot escarpment formed by the Black Hand strata effectively checked the ice-movement and only the outer rim, two to five miles in width, was covered by ice. South and east of the ice-margin the original Tertiary valleys were variously modified by accelerated stream-erosion and stream-reversal. The valley bottoms were altered by the accumulation of glacial outwash, by its subsequent partial removal, and by proglacial lake deposits.

Just south of Lancaster, Ohio, lies the unglaciated part of this terrain, commonly called the "Hocking Hills". This area covers about 125 square miles characterized by rugged topography with sharp ridges, cliffs, gorges, rock ledges, grottos, and steep talus-slopes not infrequently bearing huge blocks of sandstone that are on their way to the valley bottom. The Hocking Hills are lithologically and topographically distinct from the rounded hills of the plateau eastward and southward, and totally different from the low-lying till plains and moraines to the north and west.

As an intricate complex of plant environments the region is equally unique in this part of Ohio. The porosity of the upper forest soils and of the underlying rocks permits the rapid percolation and accumulation of water during rains and results in the slow and nearly constant seepage of water from lower rock surfaces and talus. There is, therefore, a continuously available water-supply in the substrate at lower levels. At the same time droughts are frequent on the upper ledges and ridge tops. Here shallow-rooted plants are annually subjected to various degrees of desiccation, but even here the deep-rooted plants may have an adequate water-supply at all times if their roots penetrate the open joint planes and crevices in the rocks beneath.

Any experienced field biologist entering the Hocking Hills would at once surmise that here is not only a region of concentration of most of the present-day species of central Ohio, but also a habitat-complex where species that were once widespread in Ohio during prehistoric times might have readily survived. Such a surmise has been abundantly justified by the reports of collectors of plants and animals during the last three-quarters of a century.

In addition to the modern species there are many relic species that entered the region from the south, possibly during warm preglacial or interglacial times. During glacial times, when somewhat colder weather prevailed, boreal species became established. Others must have come into the area when these forests had been succeeded by hemlock and white pine. And still more recently during the post-glacial drier and warmer interval many grassland species became established on the drier sites, when prairie vegetation advanced from the central Mississippi valley into Ohio. By the time of settlement by white men these prairie areas were greatly reduced in area.

The valley chosen for these microclimatic studies is a branch of Clear Creek, known among local scientists as "Neotoma". (The name given to the valley is the generic name of the Allegheny

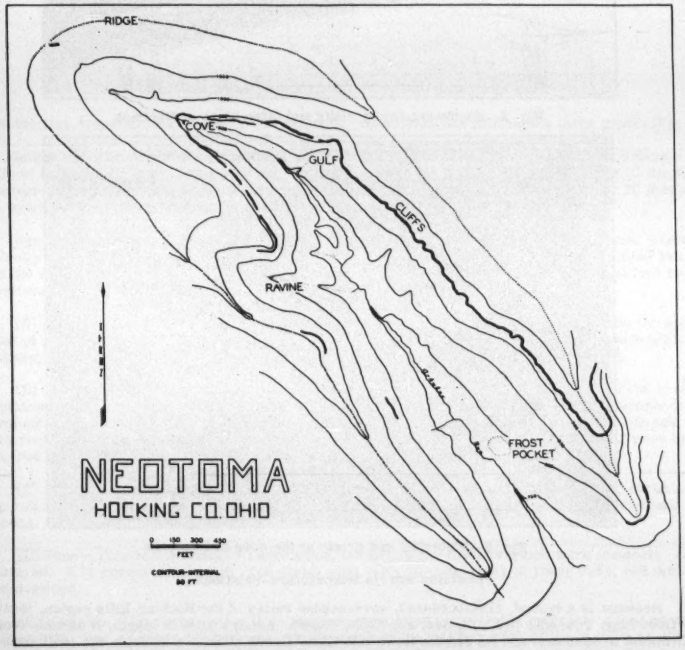

Fig. 1--Contour-map of Neotoma

wood-rat, as this is one of the few outlying stations at which this mammal occurs.) This valley was chosen because of the protection afforded the instruments and equipment, and the not infrequent help given by the owners, Edward S. Thomas and Merlon McInturf. A more complete account of these studies will be published as a Bulletin of the Ohio Biological Survey.

Fig. 2--Southwest-facing cliffs and talus slope at Neotoma

Fig. 3--Waterfall and grotto at the cove at Neotoma

Neotoma and its temperature-relations

Neotoma is a typical, cliff-bordered, cove-headed valley of the Hocking Hills region, located in Good Hope Township (NW 1/4, Sec. 16, T13N, R18W). About a mile in length, it extends from northwest to southeast and its stream flows into Clear Creek about a mile from the confluence of Clear Creek and the Hocking River. There is a side ravine heading westward from the main valley, a half mile from its mouth (Fig. 1).

On the southwest-facing side are 50-foot cliffs, rising vertically from the upper talus-slope, and extending almost continuously the length of the valley (Fig. 2). On the northeast-facing side, only remnant cliffs persist. These are discontinuous and do not exceed 30 feet in height except at the valley head. The ridge top here is sharp, and typical of most of the ridge tops of the region.

These vertical cliffs converge at the valley head, forming a rock-rimmed cove, into which

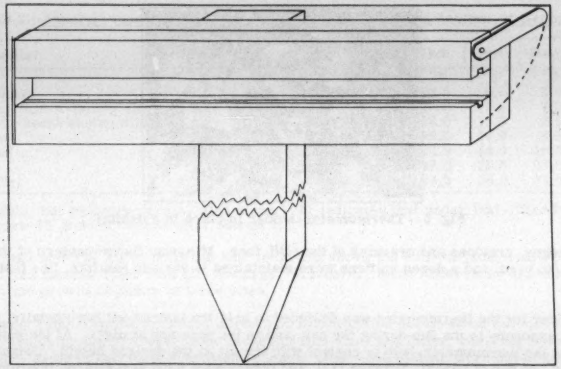

Fig. 4--Wooden holder for standard Weather-Bureau thermometers

Arbutus Run drops 40 feet. Back of the waterfall, weathering has produced a large grotto (Fig. 3).

Below the cliff bases are steep talus slopes, on which are scattered sandstone boulders. The soils of both upland and talus slopes are derived from the sandstone. The lower third of the valley, however, is filled with valley train gravels and lacustrine deposits to a depth of 75 or 80 feet near the mouth of the valley. Maximum relief is 345 feet.

Vegetation-cover--The forest of Neotoma is all secondary, although part of the area was apparently selectively cut. No cutting, however, has taken place in the valley for the past 25 years, and the species of the original forest are beginning again to attain dominance. At least five communities form the present vegetation-cover.

(A) Oak chestnut--This association, which occupies the southwest-facing slope and the upper talus of the northeast-facing slope, is dominated by white, black, and chestnut oaks, with bitternut-hickory, sourwood, and sour gum less prominent. Formerly chestnut was a dominant.

(B) Mixed mesophytic--This association occupies the northeast-facing slopes and the lower southwest-facing slopes coveward. Where least disturbed, it is characterized by the presence of hemlock, beech, birch, and tulip. Associated species include red and sugar maple, white oak, butternut, cherry birch, red oak, and sour gum. In its present condition in areas that were clear-cut, red maple and sweet birch are still the dominant species.

(C) Mixed oak--This association, dominated by black, scarlet, and chestnut-oaks, occupies the ridges. Subordinate species are chestnut (sprouts), scrub and pitch pine, and occasional aspens.

(D) Pine--This is a secondary association, occupying the uplands which were formerly pastured. It is composed of pitch and scrub pine, with an understory of young oaks, red maple, and dogwood.

(E) Pasture--The lower valley is in pasture, now largely dominated by broom grass on the slopes, with blue grass in the bottoms. On the talus at the western edge of the pasture an alder-thicket marks a seepage-area.

Temperature-measurements--Data concerning minimum and maximum temperatures, their duration and season of occurrence and the length of the frost-free period in various habitats in the valley for 1941 form the basis of the following discussion. These data were obtained from about 100 stations in the valley by placing standard Weather Bureau minimum thermometers in a specially constructed holder (Figs. 4 and 5), three to six inches above the substrate, that is, above bare soil, sod, bare rock, or leaf litter, depending on the site. Stations are located at various elevations on the slopes, on the ridges, in the valley bottom, in the cove, on the cliff top, cliff-

Fig. 5--Thermometer-holder in place in a habitat

faces and ledges, crevices and crannies of the cliff face. Min-max thermometers of the Six's type were also used, and a dozen stations were maintained in various habitats, five feet above the ground.

The holder for the thermometer was designed to hold the instrument horizontally, shelter it from direct exposure to the Sun during the day, and to the open sky at night. At the same time the holder keeps the thermometer-bulb in contact with the air at the desired height. Geiger [3 of "References" at end of paper], Turnage [13], and others have used unsheltered instruments but our experiments indicate that readings obtained from instruments in this holder are more satisfactory than those obtained either from completely exposed thermometers, or from thermometers in standard shelters.

Variations in minimum temperatures recorded by three thermometers, variously sheltered, and one exposed to the open sky are shown in Table 1. One thermometer was in the above-described holder, another in a shelter similar to the standard Weather Bureau type, and a third was placed beneath a board which was held eight inches above the ground by four stakes. The exposed instrument was placed on top of the board, face up, in one of the holders. All four instruments were within a few feet of each other. As a result of this experiment we concluded that the figures recorded by the instruments in the holder represent the most accurate measure of air-temperature, since the exposed thermometer is supercooled and those inside other shelters were excessively sheltered.

Minimum temperatures--Annual minimum temperatures in different habitats of the valley varied widely in the winter of 1941-42. The effect of cold-air drainage, as has been pointed out by a number of workers, is conspicuous in the lowlands, but other variations must be attributed to other phenomena. Temperatures in a frost-pocket in the lower valley, in crevices, grottos and the

Table 1--Comparison of temperatures recorded by variously sheltered thermometers

Date[a]	Exposed to sky	In therm. holder	In shelter of W.B. type	Beneath board
1942	°F	°F	°F	°F
Jan. 3	14.5	15.5	21.5	18.5
10	-27.0	-25.0	-20.0	-20.0
17	- 7.5	- 7.5	- 1.5	- 5.0
24	15.5	16.0		17.5
31	12.5	13.5	17.5	
Feb. 7	-11.0	- 7.0	- 1.5	- 4.0
14	0	3.5	9.0	6.5
21	- 7.5	- 4.0	2.0	- 1.0
28	1.0	4.0	9.0	7.5
Mar. 14	21.5	22.5	26.0	24.5
21	16.5	19.0	22.5	22.0
28	15.5	17.5	21.0	21.0
Apr. 4	16.0	18.5	23.0	22.0
11	29.0	31.5	33.0	33.0
18	18.5	20.0	24.5	23.5
25	16.5	19.5	25.0	23.5

[a] The date given is that on which the instruments were read. The temperatures are the minimums recorded during the preceding six or seven days.

Table 2--Absolute monthly minimum temperatures at several habitats at Neotoma

Habitat	Mar.	Apr.	May	Sep.	Oct.	Nov.	Dec.	Jan.
	°F	°F	°F	°F	°F	°F	°F	°F
Frost pocket	1.5	6.0	23.0	29.0	23.5	9.0	3.0	-25.0
Lower northeast-facing slope	4.5	10.5	31.0	38.0	30.0	13.5	7.5	-19.5
Upper northeast-facing slope	4.5	14.5	34.0	42.5	34.0	15.0	8.5	-15.5
Ridge top	3.5	13.5	36.0	44.5	35.0	14.5	6.5	-19.0
Covehead	9.0	21.0	37.0	40.0	32.0	16.5	10.0	-16.0
Crevice	18.5	28.0	46.0	54.0	45.0	30.0	27.0	+10.0
Leaf-litter	33.0[a]	36.0[a]	40.0[a]	52.0	46.5	36.0	31.0	+32.5

[a]No data, but evidence accumulated since 1941 indicates that under leaf-litter temperatures below 33°F do not occur after March 1.

cove, and in the layer of air beneath the leaf mold and above the soil-surface, exhibit variations that result from factors other than air-drainage. Moreover, these differences are clearly correlated with the growth of plants in these sites.

The lowest temperatures recorded during the investigation occurred on the morning of January 8, 1942. Previous to the cold wave, four inches of fine snow had fallen, covering some of the thermometers to a depth of two inches or slightly more; other instruments were not covered. The instruments, read on January 10, revealed a wide variation in minimum temperatures at different habitats in the valley, not all due to presence or absence of snow-cover, or directly to cold-air drainage.

The absolute minimum of -25°F was recorded in the frost-pocket. Under the blanket of snow, minima of -5° to -15°F were noted. Minimum temperatures on the upper slopes were -15° to -17°F; on the ridges -19°F; in the cove -16°F; in the crevices, ledges and crannies of the cliff face, +10° to +14°F; beneath the leaf litter at the only station established at the time, +32.5 F. The Weather Bureau record at Lancaster for the date was -18°F.

These extreme variations in the various habitats were noted regularly, as indicated in Table 2, where monthly minimum temperatures are recorded for several habitats.

Maximum temperatures--The annual maximum temperatures recorded in various habitats likewise show a wide variation. Moreover, they are not attained in mid-summer but in some habitats occur in the spring and in others in the late summer. Several habitats are compared in Table 3 by months through 1941.

It will be noted that the Weather Bureau station was the only one reaching a maximum in July. In general, maximum temperatures in climax or fairly mature forests of the valley are recorded in the spring, when there is abundant water. Thus the effects are not detrimental to plant-growth. In pioneer communities or in young forest, the maxima are attained in the late summer, when water is much less abundant, or drought-conditions prevail. Moreover, these temperatures are much higher, reaching as much as 120°F on the cliff-top.

Table 3--Absolute monthly maximum temperatures in several habitats at Neotoma, 1941, and monthly maxima recorded by the Lancaster Weather Bureau station

Habitat	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
Cliff top[a]	68	71	85	102	109	110	113	117	115	107	84	73
Cove	49	43	49	80	68	74	76	76	77	73	57	55
Ridge top[b]	57	61	65	93	92	92	95	98	88	89	75	65
Red maple[b]	56	54	61	89	86	87	87	88	83	81	69	62
Chestnut oak[b]	55	61	64	90	89	87	90	93	86	86	76	67
Hemlock[b]	59	54	58	83	87	85	89	90	82	85	71	65
Crevice[c]	...	...	...	...	...	112	88	88	86	86	76	72
Crevice[d]	...	...	...	...	...	73	78	85	76	72	57	53
Grotto	...	...	...	...	...	72	73	75	72	71	60	57
Leaf-mold	...	...	...	...	...	71	72	77	73	70	58	51
Lancaster W. B.[b]	56	60	62	88	92	95	102	85	92	71	73	66

[a]Thermometer unsheltered. [b]Five feet above soil-surface. [c]In southwest-facing cliff. [d]In northeast-facing cliff.

Frost-free period--The term "frost" is here used with reference to conditions prevailing when the thermometer reads 32°F or lower. "Frost" thus is not distinguished from "freeze", but because it was not possible to be in the field when the formation of ice-crystals occurred, it seems expedient to use the temperature 32° as an indicator of frost. Perhaps, in ecological meteorology, 29° or 30° would be a much more desirable criterion delimiting the effective frost-free period.

Neotoma is located within the area designated in the 1942 Yearbook of Agriculture [14] as having an average frost-free period of 160-170 days. In the 48 years for which records of weather have been kept, the period at Lancaster has varied from 123 to 202 days. According to the Weather Bureau records [2,15], the last frost in spring may occur as early as April 8, and as late as May 23. First frosts in fall occur between September 2 and November 6.

On June 23, 1918, however, a minimum temperature of 40°F was reported by the observer [7] at Lancaster, who remarked, "Considerable frost-damage to corn and tender vegetables". Thus, the Weather Bureau interpretation of the observer's data is misleading (that is, the last frost in spring at Lancaster occurs between April 8 and May 23). Of considerable importance to agriculture is a knowledge of frost-phenomena, and it seems necessary to obtain data concerning them in the plant environment itself. Only in this manner can reliable information be obtained concerning the time, distribution, and duration of frost-conditions.

That the Weather Bureau data do not reflect actual conditions in the field is further indicated by the data in Table 4, in which several stations at Neotoma are compared. Not only do the lengths of the periods differ substantially, but the dates of the last frosts in spring and the first frosts in fall are at great variance from those obtained by the Weather Bureau method of determining temperatures.

Table 4--Lengths of frost-free periods at several habitats at Neotoma in 1941, and at Lancaster Weather Bureau

Habitat	Date last spring frost	Date first autumn frost	Number frost-free days
Frost pocket	May 25	Sep. 26	124
Lower slopes	May 14	Oct. 11	150
Upper slopes	Apr. 22	Oct. 29	190
Some ridge tops	Apr. 3	Oct. 29	209
Cove	Apr. 3	Nov. 11	221
Crevice	Apr. 3	Nov. 25	235
Grotto	Apr. 3	Dec. 13	254
Lancaster Weather Bureau	May 5	Sep. 26	144

The intensity of the first and last periods of sub-freezing temperatures, as well as their duration, is also of significance ecologically. Although only a beginning has been made in the study of these factors, Table 5 indicates the intensity and duration of some early frosts in fall at the several stations in 1941, as recorded by thermographs inside shelters similar to the standard Weather Bureau type.

Table 5--Number of hours of temperature below 32°F and the minimum temperatures at several dates in the fall of 1941 (inside shelter)

Habitat	October 11		October 24		November 15		November 25	
	Hours dur.	Min. temp.	Hours dur.	Min. temp.	Hours dur.	Min. temp.	Hours dur.	Min. temp.
		°F		°F		°F		°F
Frost pocket	5.0	29.0	7.0	29.0	8.0	26.0	15.0	15.0
Northeast-facing slope	0.0	35.0	0.0	33.0	0.0	32.5	17.0	15.0
Cove	0.0	34.0	0.5	32.0	4.0	29.0	17.0	17.0
Ridge top	0.0	38.5	0.0	40.0	0.0	36.0	10.5	19.0

Table 6 shows the variation in total hours of temperatures below 32°F in the same four habitats during two critical spring months.

Table 6--Number of hours of temperatures below 32°F at four stations during March and April, 1942

Habitat	March	April	Habitat	March	April
Frost pocket	256	57	Northeast-facing slope	196	17
Cove	220	12	Ridge top	155	20

Atmometer measurements

Diversity of microclimatic conditions is an important factor in the water-relations of habitats of plants and animals within an area. In the studies of water-relations at Neotoma, data on soil-moisture variations at several stations, precipitation-data at three stations, and recording-hygrometer data at four stations have been obtained at various times. The most extensive study has been the measurement of relative rates of evaporation of water from porous-clay atmometers at a number of stations.

The apparatus employed for this study consisted of a white Livingston atmometer bulb attached to a Woulff bottle reservoir by means of a glass tube with an S-shaped mercury valve. From 15 to 42 of these atmometers were placed singly in a variety of locations in the valley in different years. The weekly water-loss was determined by measuring the volume of distilled water necessary to fill the reservoir to a mark. The instruments were placed on the ground in each location, the porous-clay bulbs being held at a height of 15 to 18 inches above the soil-surface. Measurements were made from late spring to early autumn in 1940, 1941, and 1942.

We have restricted our study to a comparison of the aerial factors in the environment of plants in various habitats. The misleading term "evaporating power of the air", as measured by atmometers, has little direct relationship to transpiration or evaporation from land and water [10]. At the same time the method of Thornthwaite and Holzman [9,11] for measuring evaporation is not feasible for use at near-ground levels in small restricted habitats within larger areas. To the extent of their reliability, atmometer-readings do indicate the combined effects of vapor-pressure, wind-velocity, temperature, and illumination at the places in the habitats where the instruments are located. Variations of these factors are important in habitat water-relations. Differences in water-loss from the several atmometers certainly reflect differences in the microclimates of the various parts of the valley. To analyze the atmometer-data in detail, additional instruments are needed.

Table 7 gives, for several stations, relative values of total evaporation from atmometers for the entire time of observation in 1940 and 1941, and for one selected week for each year when contrasts were extreme.

The first three creek-bottom stations have rather close canopies of beech, birch, tulip, and red maple. The station near the cove is extreme in that independent observations indicate that light-intensities are lowest, air-movement least, and summer vapor-pressures highest of all the stations. The Hemlock Creek bottom station is somewhat less extreme in all respects. The

Table 7--Relative evaporation from atmometers
(In 1940 the instruments were set out after leaves developed; in 1941 about four weeks before the leaves developed)

Habitat	Total relative evaporation for the entire period of time in the field		Relative evaporation for one selected week	
	June 8 - Sep. 29, 1940	Apr. 27 - Oct. 12, 1941	July 27, 1940	Sep. 6, 1941
Cliff-top station	100	100	100	100
Ridge-top station	68.5	70.6	46.9	62.6
Talus-slope stations				
Chestnut oak	52.2	56.9	54.2	41.7
Hickory	47.8	51.0	37.2	35.1
Creek-bottom stations				
Beech	30.4	31.3	21.1	13.4
Hemlock	19.5	25.5	11.1	5.6
Cove	10.9	19.6	1.7	1.3

Beech Creek bottom station is in the lower and wider portion of the valley where the canopy is less dense, air- and surface-temperatures higher during the daytime, and air-movements much more pronounced than toward the valley head.

All stations on the talus slopes showed higher relative evaporation from atmometers than creek-bottom stations. The northeast-facing talus (hickory) station and the southwest-facing (chestnut oak) station are 180 and 130 feet, respectively, above the creek-bottom (beech) station. The canopy is more or less open and chestnut-oak and hickory are the dominant trees. Air-movements are here much more pronounced than at the creek-bottom stations.

The ridge-top station is 205 feet above the beech station. The canopy is rather open, formed by a stand of chestnut oak. Wind from any direction moves readily past this station and vapor-pressures are somewhat lower during the summer than at lower elevations.

The cliff-top station consistently had the highest rate of relative evaporation. It is an extreme situation in that there is no tree canopy above the station, it is shaded only for a short time after sunrise and winds from the south, east, and west strike the station without obstruction by vegetation. Convection-currents are at a maximum here due to the heating of the exposed rock surface, and the coefficient of turbulent transfer is probably greater than at any other station in the valley.

The differences in total relative evaporation at stations in 1940 and 1941 are due partly to the difference in the length of time the atmometers were in the field during the two seasons. Data reported for 1940 were obtained after the canopies were closed by leaf growth. In 1941 the instruments were set out several weeks before canopy closure.

Table 8 gives the relative effect of the canopy on evaporation at a number of stations using the cliff-top station, with no canopy, as a standard. The data are based on the total evaporation during a five-week period following complete leaf emergence.

Table 8--Relative effect of the leaf canopy on evaporation from atmometers

Station	Relative effect of the canopy
Cliff top	
Cliff (standard, no canopy)	1.00
Ridge top	
Southwest ridge	1.15
Talus slope	
Hickory	1.24
Creek-bottom stations	
Beech	1.50
Hemlock	1.76
Cove	1.80

These data are qualitatively in agreement with observable differences in the density of canopies at the various stations. It seems reasonable to predicate that the more dense the canopy, the lower the surface-temperatures, the less the convection-currents and air-turbulence, and the less the differences in vapor-pressure between moist surfaces and the atmosphere.

Comparison of relative rates of evaporation from atmometers with other measurable factors contributes to the recognition and separation of microclimatic areas in the valley. Such data may also be useful in the interpretation of relative effects of seasonal changes on phenomena of evaporation. It is clearly recognized that evaporation from atmometers is not necessarily related to transpiration, or to evaporation from the soil, even though it is affected by most of the factors that limit these processes.

The measurement of light

Measurements of light-intensity, light-duration, spectral quality, and total radiation in the visible portion of the spectrum are desirable in comparing natural habitats. Many devices have been made to measure the light-factor. Photographic papers of various sensitivities and exposed with various instruments have been used. Numerous limitations to this method have been pointed out by Klugh [6] and Braid [1]. The rates of photochemical reactions [1] may be used but have serious limitations. Instantaneous readings can be obtained from photometers using photoelectric

cells. Sprague and Williams [8] describe a portable light-recorder utilizing a phototube that may prove practical for field-use. Perhaps the most useful data can be obtained by use of one of the several types of pyrheliometers because they give continuous records of light-intensity [4,5]. In the pyrheliometer (a thermopile in which alternate junctions are in contact with white and black rings) an electrical potential results which varies with the difference in temperature between the two rings. The greater the light-intensity, the greater the difference of temperature. According to the manufacturer, the two surfaces absorb long-wave radiation equally well and the white surface reflects all parts of the visible spectrum. By means of a calibration furnished by the manufacturer, it is possible to calculate light-intensities expressed in gm cal/cm^2/min from the recording-potentiometer readings in millivolts. By use of filters the intensity in various narrower ranges of the spectrum may be measured [4]. The pyrheliometer may be kept at right-angles to the incident rays of the Sun manually or by mechanical devices. Or it may be mounted permanently at right-angles to the Earth's radius, in which case it measures light-intensity at horizontal incidence. The United States Weather Bureau uses the latter method. Pyrheliometers are compact but the necessary recording apparatus is bulky, expensive, and requires a source of electric current.

Thut [12] described a light-meter designed for use in the field or laboratory, which is both compact and inexpensive. He said: "Its principle is that of a metal, spiral radiation pyrometer made sensitive principally to the visible spectrum. Environmental temperature-fluctuations are nullified by using a second spiral as the reference-point for the first. These coils are enclosed in a frosted-glass globe. The arm, activated by the first spiral, records on a clock-operated drum."

The Thut instrument consists of a 3/16-inch wide black coil, the activator-coil, attached at the inner end to the top of a metal shaft which extends through a metal tube. A 5/16-inch wide white coil, the reference-coil, is attached at the inner end to the tube below the black coil. The outer ends of the coils are joined by a material of low heat-conductivity. An indicator is attached to the lower end of the shaft. The coils are of bimetal. (The coils were obtained from the H. A. Wilson Company, Newark, New Jersey. No. TMP 97 is the 3/16-inch coil; No. TMP 98 is the 5/16-inch coil.) When the temperature of these two coils changes at equal rates there is no movement of the shaft. As one coil attains a higher temperature than the other, the shaft rotates, the amount of rotation depending upon the relative difference in temperature.

Several of these instruments were made following directions and drawings kindly furnished by Dr. Thut. They were tested over wide ranges of temperature and light-intensities. If no abrupt changes in temperature occur these instruments proved satisfactory. However, abrupt changes in temperature (such as a change from temperature in a room to a refrigerator) caused a wide deflection of the indicator. As noted above, the reference-coil is larger than the activator-coil and is mounted below it on a metal tube. The masses of the two coils plus their mountings differ widely. Consequently, even when exposed to changes in long-wave radiation only, their temperatures do not change at equal rates. Since the operation of the instrument is dependent upon differentials in temperature, this is a serious objection.

To avoid the above-described difficulty a modification in the design of the Thut meter has been incorporated into a new instrument, which is illustrated in Figure 6. Coils of equal size, 3/16-inch wide, were used and mountings made of bakelite, a material as nearly non-heat-conducting, yet workable, as could be obtained. The white reference-coil is attached at the inner end (A) to an L-shaped mounting of bakelite (E) bolted to the base. The black activator-coil is attached at the inner end (B) to the upper end of a bakelite shaft (K) with a bakelite bearing at (J) and a brass bearing at (L). The outer ends of the coils are joined by a bakelite bar (F) with bearings at (C) and (G). Bolts (D) and (H) are attached to the coils through slots which allow for adjustment. The distance between the coils may also be adjusted by moving the white-coil mounting (E). The distance between (A) and (B) must be equal to the distance between (C) and (G). Rotation of the shaft (K) moves the attached bar (M). The direction of this movement is changed through (N) to the counter-balanced recording pen (0). A record of the pen movement is made on a revolving drum.

The white coil was prepared by painting with du Pont's "titanium white", the pigment consisting largely of titanium oxide. The magnesium-oxide-smoked surface, used in pyrheliometers, is impractical except in a sealed unit. The black coil was prepared by first coating it with a thin layer of spar-varnish, followed by deposition of lamp-black by holding it in the smoke of burning camphor. The unit is enclosed in a square box of opaque material except for the cover which is of opal glass made by the Pittsburgh Glass Company. It should be possible by substituting the proper filters for this opal-glass cover to measure the intensities of various portions of the spectrum. The field-case was constructed of "Diestock", a pressed-wood product of Masonite Corporation.

The present instrument is not usable at temperatures of 20° F and below, because as the connecting bar (F) comes into line with and passes the line (A) - (B) extended, the behavior of the rotation of the shaft changes. This can be corrected.

Slight movements of the pen occur on some nights, perhaps because of unequal rates of radiation from the two surfaces. The black coil should probably be coated with paint instead of smoke, since the smoke-particles greatly increase the radiation-surface.

Four of the instruments were completed by September 1942. They were calibrated against an Eppley pyrheliometer and found to give a substantially similar curve on clear days. On partly cloudy days the curve obtained is more nearly the average of the pyrheliometer-curve because this instrument does not react as quickly to changes in light-intensity. Trials in the field were carried out from September 26 to December 5. One instrument was placed in an unshaded field,

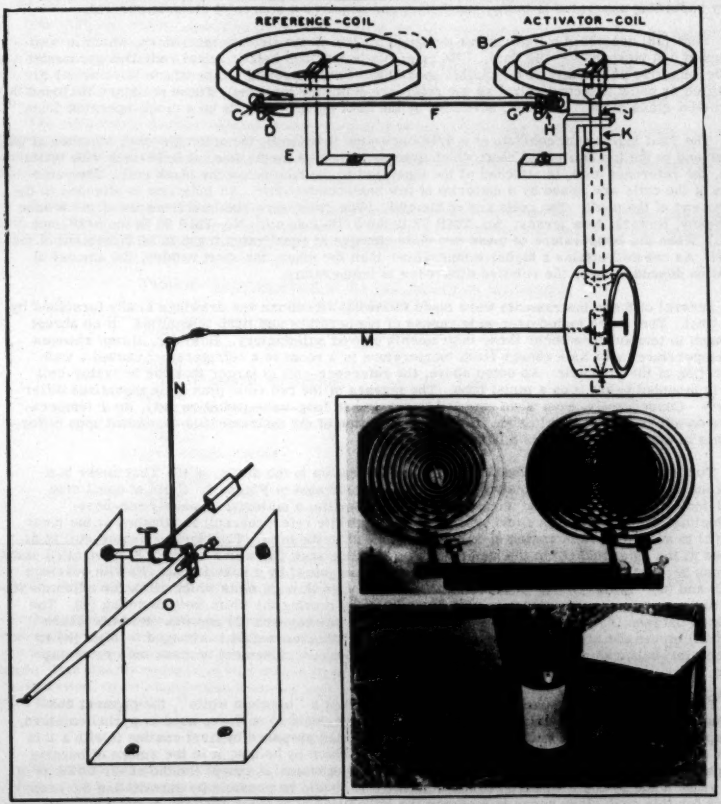

Fig. 6--Sketch of light-meter, details of coils and hook-up (inset), and light-meter in field-case with cover removed (inset)

Table 9--Light-variation in three habitats

Date	Full sunlight		Oak-chestnut			Hemlock-beech-birch-maple		
	Total	Change	Total	Change	Full sunlight	Total	Change	Full sunlight
1942	gm/cal/cm^2	pc	gm/cal/cm^2	pc	pc	gm/cal/cm^2	pc	pc
Oct. 8	411		28		7	4.9		1.2
20	381	- 7	74	16	19	5.5	12	1.4
26	346	-16	140	400	40	23.0	369	6.6
Nov. 11	314	-24	188	571	60	33.0	573	10.5

another in an oak-chestnut forest on a southwest-facing slope, one on the opposite slope, and a fourth in a hemlock-beech-birch-maple grove located on the lower northeast-facing talus. No usable records, however, were obtained from the third station.

Using factors obtained from a calibration-experiment, these records were transferred to micromax recorder paper and total radiation in terms of gm/cal/cm^2 were calculated. Table 9 shows the results for four clear days. More data will be obtained during spring and summer of 1943.

Leaf fall accounts for the increase in total solar radiation in the oak-chestnut and hemlock-beech-birch-maple locations even though the radiation in full sunlight decreased. Considering the many direct and indirect effects of solar radiation, it is clearly desirable to characterize habitats in absolute terms. Portable, inexpensive, simply operated instruments will make this possible.

Summary

This paper is a first report of a study of the microclimates of a small valley, located in a biotically and geologically distinct region in central Ohio. The conclusion has been reached that atmospheric factors are fully as significant as the soil-factors in explaining the pattern of plant-communities in a diversified area. Atmospheric factors certainly are most important in explaining the seasonal variations in plant-behavior.

Conditions of temperature surrounding living plants varied widely in various parts of the valley at all seasons of the year. These differences may be attributed in part to cold-air drainage, to snow-cover, to variations in insolation and radiation, and to physical characteristics of the substrate.

Evaporation from atmometers, placed in various habitats, furnishes data significant in the recognition and separation of microclimatic areas.

Light-conditions were measured by portable, recording, simply designed, and inexpensive light-meters using bimetallic coils as suggested by Thut. The instruments were constructed in the Ohio State University Botanical laboratories. Although only preliminary studies have been made with these instruments, the data appear to be useful in differentiating diurnal and seasonal light-regimes. The data recorded by this light-meter are comparable to those obtained from a pyrheliometer of the Eppley type.

Our data indicate different climates in three superposed layers: (1) The leaf litter; (2) the herbaceous plant; and (3) the shrub levels. The small-tree levels and the canopy levels have not been investigated.

The maximum and minimum temperatures within the lowest one-foot layer of the atmosphere vary both in degree and duration in various parts of the valley. Moreover, the time of maximum temperatures varies from April to September in the several habitats.

Observations made in standard Weather Bureau shelters contribute little to the evaluation of the climatic factors that influence the development, distribution, and persistence of plant and animal communities in local areas.

The investigation is being continued and intensified, and a report of data collected through 1943 will be presented in a forthcoming volume of the Ohio Biological Survey.

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WIND-GRADIENT OBSERVATIONS

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In our report of the work of the Soil Conservation Service evaporation-project, at the meeting in 1942, we called attention to the need for reliable observations of wind-velocity at various levels within a few feet of the Earth's surface, taken throughout the day, and at various seasons of the year to determine the character of the wind-structure during different conditions of atmospheric stability, and over different kinds of surfaces. We also pointed out the nonexistence of such observations and mentioned the difficulty of obtaining them [see 3 of "References" at end of paper].

During the last year we have devoted much effort toward getting an accurate series of wind-gradient observations that would reveal the law of wind-structure. Several hundred anemometers were checked against a carefully calibrated standard instrument, on a specially constructed eight-arm variable-speed whirler, that moved them 1/50 mile per revolution, and several were selected that were practically identical in starting speed, stopping speed, and running speed, and that would commence running at wind-velocities well under one mile per hour. The photographic recorder designed and built for recording wind-velocities at 14 different positions has already been described [1].

During the summer of 1942, a number of anemometers were rebuilt to permit the measurement of lower wind-velocities. Friction was reduced through the use of mercury-contacts and for a few days some especially good records were obtained. In the autumn several anemometers were modified to the extent of having additional cups mounted on arms that had been extended to three times the original length. These instruments would run at phenomenally low speed--about 0.30

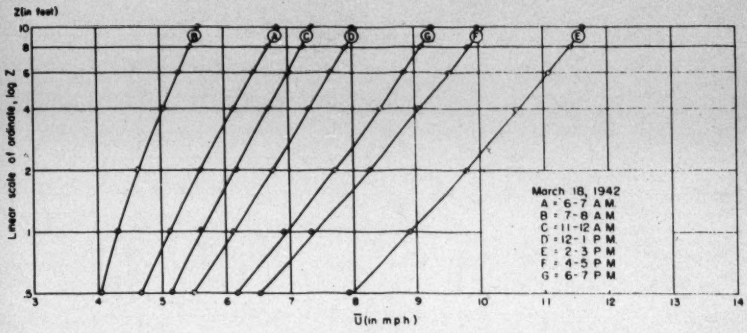

Fig. 1

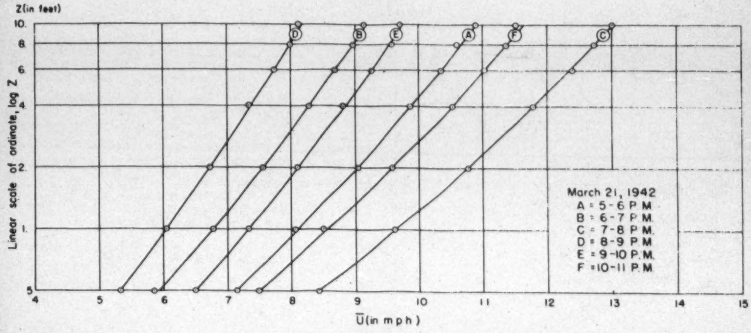

Fig. 2

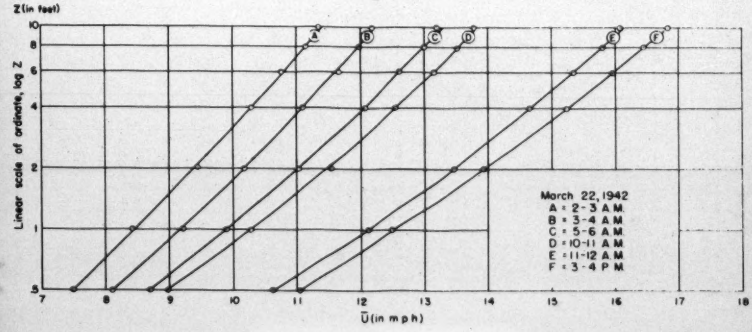

Fig. 3

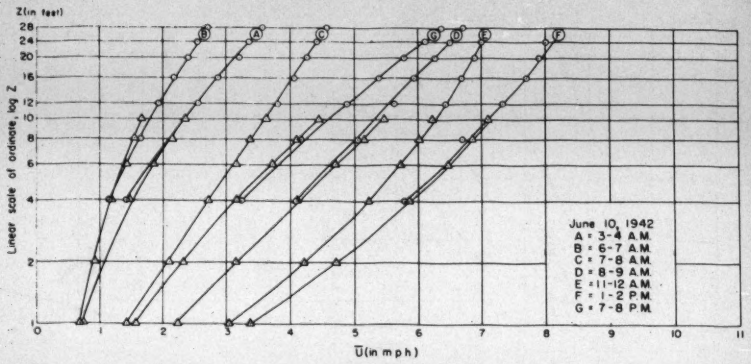

Fig. 4

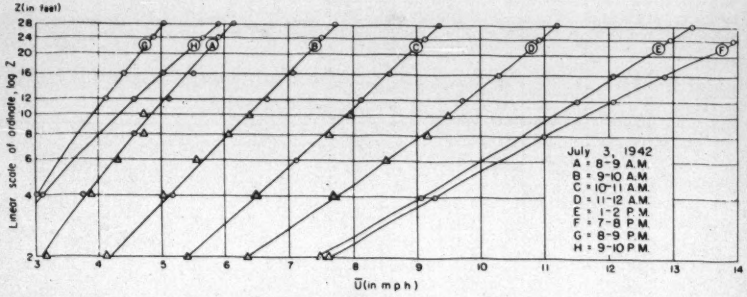

Fig. 5

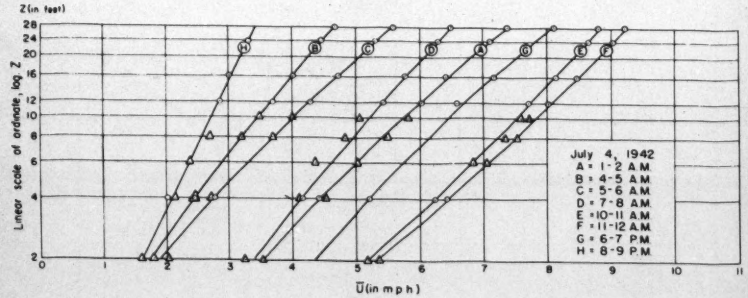

Fig. 6

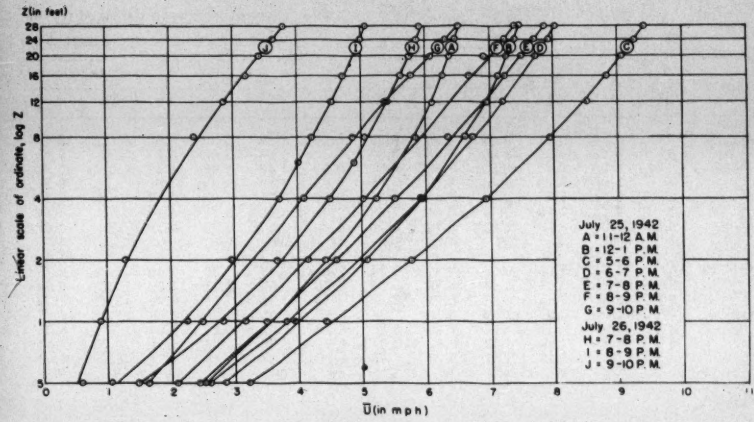

Fig. 7

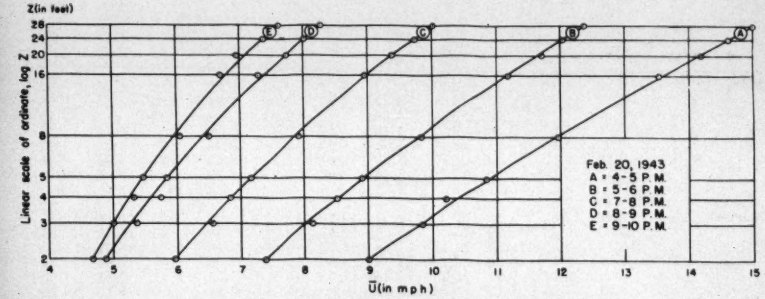

Fig. 8

mile per hour (0.13 meter per second) represented the minimum.

For more than a year wind-gradient records have been made at New Philadelphia, Ohio, with this equipment. The first installation consisted of two towers about 50 feet apart. On one tower seven anemometers were mounted at four-foot intervals above the ground, between 28 feet and four feet. On the other tower there were five anemometers at two-foot intervals, between ten feet and two feet. Two other anemometers were set nearby at 1 foot and 0.5 foot above the ground-surface. In February, 1943, 11 of the long-arm low-speed anemometers were mounted on a special tower and put into service. In addition to seven at four-foot intervals up to 28 feet, anemometers were placed at one, two, three, and five feet. On another tower nearby, standard anemometers were mounted at 24, 12, and four feet for comparison.

Despite the many precautions that were taken there are many gaps in the records, and those that were obtained are not uniformly good. However, it is usually possible to identify the periods when the anemometers were making double contacts or were missing contacts. Despitetheir deficiencies this is the first series of wind-observations ever made that shows clearly the effect of atmospheric stability on the wind-profile itself. This justifies the publication of a fairly extensive

Table 1--Wind-velocity at indicated levels

(Wind-direction, where indicated in

Date	Ht, obs'r ft	Average velocity										
		01	02	03	04	05	06	07	08	09	10	11
1942												
Mar. 18	10	6.59	10.31	9.13	8.99	9.98	10.64	6.82	5.60	6.43	.....	9.30
	8	6.48	10.10	8.89	8.82	9.82	10.46	6.69	5.48	6.33	.....	9.18
	6	6.28	9.83	8.69	8.56	9.51	10.17	6.46	5.30	6.17	.....	8.92
	4	5.96	9.36	8.26	8.13	9.05	9.67	6.13	5.03	5.89	.....	8.51
	2	5.43	8.54	7.54	7.43	8.26	8.84	5.61	4.63	5.43	.....	7.77
	1	4.78	7.59	6.74	6.61	7.33	7.85	5.12	4.31	4.99	.....	6.84
	0.5	4.24	6.66	6.02	5.79	6.54	6.89	4.67	4.03	4.55	.....	6.05
	Dir.	W	W	W	W	SW	W	SW	SW	W	.....	W
Mar. 19	10	8.64	9.98	9.82	8.97	8.34	7.51	7.77	7.66	7.40	13.08	9.75
	8	8.41	9.69	8.46	8.72	8.08	7.28	7.54	7.43	7.20	12.73	9.52
	6	8.21	9.41	8.26	8.51	7.92	7.13	7.35	7.28	6.99	12.48	9.28
	4	7.76	8.97	7.87	8.10	7.54	6.80	6.95	6.90	6.66	11.79	8.87
	2	7.08	8.21	7.15	7.40	6.85	6.18	6.32	6.27	6.07	10.79	8.08
	1	6.25	7.36	6.33	6.87	6.35	5.77	5.68	5.76	5.51	9.67	7.43
	0.5	5.50	6.49	5.65	6.22	5.66	5.20	5.14	5.19	4.91	8.58	6.63
	Dir.	W	W	W	W	W	W	W	W	W	W	W
Mar. 20	10	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	8	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	6	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	4	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	2	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	1	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	0.5	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	Dir.	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Mar. 21	10	0.96	1.50	2.14	4.21	4.62	4.03	3.22	2.26	2.45	2.08	3.09
	8	0.83	1.29	1.93	4.06	4.53	3.94	3.11	2.14	2.28	1.93	2.96
	6	0.80	1.15	1.80	3.90	4.37	3.80	2.97	.....	2.14	.....	2.70
	4	0.75	1.03	1.66	3.72	4.15	3.59	2.81	1.88	2.03	1.66	2.65
	2	0.73	1.09	1.59	3.38	3.75	3.28	2.54	1.72	1.93	1.59	2.45
	1	0.68	0.82	1.34	2.97	3.30	2.81	2.16	1.38	1.71	1.38	2.21
	0.5	0.70	0.98	1.30	2.75	3.04	2.63	2.03	1.29	1.64	1.35	2.16
	Dir.	E	SE	SE	SE	SE	E	SE	E	SE	SE	S
Mar. 22	10	10.49	10.39	11.35	12.17	12.38	13.18	12.73	12.62	11.55	10.90	13.76
	8	10.36	10.23	11.18	11.97	12.20	12.99	12.23	12.48	11.40	10.72	13.50
	6	10.18	9.93	10.80	11.65	11.84	12.60	11.89	12.12	11.04	10.39	13.13
	4	9.61	9.49	10.28	11.09	11.30	12.04	11.35	11.56	10.49	9.90	12.53
	2	8.84	8.67	9.44	10.17	10.36	11.02	10.41	9.52	9.61	9.11	11.53
	1	8.53	7.95	8.43	9.20	9.26	9.88	9.36	9.41	8.59	8.10	10.26
	0.5	7.23	7.05	7.49	8.10	8.27	8.69	8.34	8.41	7.64	7.13	8.97
	Dir.	W	W	W	W	W	W	W	W	W	W	W
Mar. 23	10	6.68	5.84	.....	8.51	9.93	8.59	9.13	8.54	9.21	9.30	.....
	8	6.58	5.77	.....	8.26	9.66	8.36	8.94	8.39	9.06	9.06	.....
	6	6.37	5.55	.....	8.03	9.36	8.13	8.67	8.13	8.77	8.80	.....
	4	6.08	5.30	.....	7.67	9.00	7.72	8.26	7.80	8.38	8.39	.....
	2	5.55	4.86	.....	6.97	8.23	7.02	7.54	7.13	7.69	7.69	.....
	1	4.96	4.26	.....	6.35	7.67	6.33	6.71	6.32	6.77	6.84	.....
	0.5	4.41	3.80	.....	5.74	6.64	5.61	5.91	5.58	6.05	5.96	.....
	Dir.	W	W	.....	W	W	W	W	W	W	W	.....
Mar. 24	10	2.14	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	8	1.97	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	6	1.82	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	4	1.56	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	2	1.30	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	1	1.05	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	0.5	0.88	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	Dir.	W	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Mar. 25	10	2.60	.....	1.43	2.18	1.15	1.45	1.72	1.46	1.43	.....	4.05
	8	2.42	.....	1.04	2.03	1.01	1.15	1.38	1.34	1.29	.....	3.98

in miles per hour, New Philadelphia, Ohio

line "Dir.," is at the 28-foot level)

for hours ending at

Noon	13	14	15	16	17	18	19	20	21	22	23	24
7.38	8.00	10.12	11.60	11.00	9.92	9.64	9.21	9.44	9.23	11.14	9.96	7.72
7.25	7.90	9.96	11.43	10.85	9.78	9.51	9.10	9.31	9.16	10.95	9.78	7.52
7.02	7.67	9.67	11.07	10.58	9.51	9.23	8.85	9.05	8.87	10.61	9.51	7.31
6.69	7.31	9.23	10.58	10.10	9.03	8.82	8.43	8.62	8.48	10.13	9.08	6.95
6.17	6.73	8.44	9.77	9.26	8.29	8.05	7.71	7.90	7.76	9.23	8.31	6.33
5.61	6.10	7.69	8.90	8.34	7.54	7.23	6.90	7.18	7.10	8.27	7.43	5.71
5.14	5.48	6.85	7.92	7.46	6.66	6.42	6.17	5.97	6.35	7.33	6.59	5.09
SW	SW	W	SW	SW	SW	SW	SW	SW	W	SW	W	W
10.89	11.12	12.43	12.94	13.04	13.09	12.12	9.63	6.15	2.34	.....	.....	.....
10.63	10.84	12.10	12.63	12.76	12.78	11.79	9.16	5.97	2.11	.....	.....	.....
10.34	10.56	11.77	12.33	12.42	12.42	11.48	8.90	5.89	2.03	.....	.....	.....
9.87	10.07	11.26	11.74	11.81	11.84	10.95	8.49	5.60	1.74	.....	.....	.....
8.99	9.21	10.33	10.77	10.74	10.77	9.96	7.71	5.04	1.51	.....	.....	.....
8.29	8.34	9.31	9.67	9.96	10.05	9.25	7.15	4.72	1.14	.....	.....	.....
7.40	7.45	8.26	8.51	8.97	8.97	8.31	6.42	4.21	1.15	.....	.....	.....
W	W	W	W	W	W	W	W	W	W	.....	.....	.....
3.67	5.70	5.99	7.15	6.71	5.45	5.74	5.81	4.31	2.00	1.46	1.14	0.70
3.56	5.58	5.87	7.00	6.58	5.25	5.58	5.48	4.15	1.74	1.24	0.80	.....
3.42	5.40	5.66	6.80	6.33	5.06	5.35	5.43	3.95	1.59	1.14	0.70	.....
3.28	5.20	5.35	6.49	6.08	4.84	5.09	5.15	3.77	1.04	0.78	0.60	.....
2.97	4.78	4.96	5.94	5.58	4.46	4.63	4.72	3.42	1.10	0.68	0.62	.....
2.66	4.26	4.44	5.34	5.14	4.06	4.21	4.34	3.02	0.80	0.62	.....	.....
2.47	3.95	4.13	4.94	4.83	3.82	3.92	4.01	2.81	0.70	0.63	.....	.....
SE	SE	SE	SE	SE	SE	SE	SE	SE	SE	E	E	E
4.55	4.84	4.62	4.21	10.36	10.56	10.89	9.15	12.99	8.12	9.71	11.51	12.01
4.37	4.68	4.44	4.03	10.05	10.33	10.59	8.95	12.71	7.98	9.59	11.35	11.82
4.10	4.42	4.13	3.77	9.78	10.03	10.33	8.70	12.37	7.74	9.26	11.04	11.45
3.95	4.22	3.92	3.61	9.36	9.54	9.87	8.29	11.77	7.35	8.82	10.51	10.92
3.64	3.90	3.63	3.37	8.56	8.75	9.03	7.57	10.77	6.73	8.10	9.59	10.64
3.33	3.61	3.37	3.07	7.82	7.88	8.07	6.77	9.62	6.05	7.31	8.51	9.08
3.17	3.38	3.17	2.81	6.99	6.95	7.15	5.84	8.43	5.34	6.49	7.49	8.05
SE	S	S	S	SW	W	W	W	W	W	W	W	W
16.06	16.39	15.98	16.52	16.80	16.04	14.65	15.15	13.08	12.01	10.41	8.43	7.86
15.78	16.01	15.68	16.13	16.42	15.62	14.25	14.72	12.79	11.77	10.13	8.26	7.66
15.33	15.55	15.27	15.67	15.93	15.23	13.83	14.30	12.38	11.41	9.87	8.03	7.43
14.64	14.81	14.61	14.97	15.22	14.57	13.24	13.64	11.91	10.94	9.49	7.64	7.11
13.45	13.52	13.34	13.69	13.93	13.30	12.10	12.42	10.79	9.87	8.58	6.89	6.48
12.12	12.25	11.99	12.32	12.50	12.04	11.07	11.36	9.95	9.06	7.95	6.35	5.84
10.61	10.75	10.41	10.84	11.04	10.59	9.80	10.12	8.99	8.12	7.15	5.76	5.24
W	W	W	W	W	W	W	W	W	W	W	W	W
.....	14.40	.....	.....	.....	.....	.....	13.03	8.10	3.75	2.90	2.70	2.80
.....	14.05	.....	.....	.....	.....	.....	12.71	7.90	3.61	2.76	2.50	2.65
.....	13.65	.....	.....	.....	.....	.....	12.32	7.59	3.40	2.51	2.29	2.45
.....	13.04	.....	.....	.....	.....	.....	11.86	7.30	3.25	2.42	2.08	2.19
.....	11.99	.....	.....	.....	.....	.....	10.77	6.58	2.88	2.05	1.82	1.85
.....	10.82	.....	.....	.....	.....	.....	10.13	5.86	2.29	1.71	1.41	1.40
.....	9.62	.....	.....	.....	.....	.....	9.06	5.27	2.05	1.51	1.29	1.24
.....	W	.....	.....	.....	.....	.....	W	W	W	W	W	W
.....	.....	.....	.....	5.82	5.61	5.19	4.01	2.21	.....	.....	.....	.....
.....	.....	.....	.....	5.74	5.53	5.08	3.90	2.05	.....	.....	.....	.....
.....	.....	.....	.....	5.56	5.34	4.91	3.74	1.76	.....	.....	.....	.....
.....	.....	.....	.....	5.37	5.17	4.72	3.56	1.55	.....	.....	.....	.....
.....	.....	.....	.....	5.04	4.83	4.37	3.20	1.22	.....	.....	.....	.....
.....	.....	.....	.....	4.58	4.36	4.00	2.73	0.93	.....	.....	.....	.....
.....	.....	.....	.....	4.15	3.92	3.67	2.54	0.89	.....	.....	.....	.....
.....	.....	.....	.....	W	W	W	W	W	.....	.....	.....	.....
.....	6.28	5.71	7.10	6.07	6.84	6.85	4.91	4.37	4.05	3.61	2.57	4.93
.....	6.22	5.63	6.95	5.96	6.68	6.71	4.77	4.19	3.85	3.43	2.40	4.77

Table 1--

Date	Ht, obs'r ft	Average velocity										
		01	02	03	04	05	06	07	08	09	10	11
1942												
Mar. 25	6	2.24	.....	0.91	1.92	0.96	1.03	1.20	1.17	1.19	.....	3.82
	4	2.03	.....	0.82	1.66	0.80	0.77	1.03	0.98	1.15	.....	3.54
	2	1.66	.....	0.72	1.29	0.65	0.63	0.89	0.83	.....	.....	3.48
	1	1.25	.....	0.62	0.91	0.60	0.60	0.62	0.65	1.04	.....	3.12
	0.5	1.17	.....	0.60	0.82	.....	0.60	0.60	0.63	1.01	.....	2.90
	Dir.	E	.....	E	E	E	E	E	E	E	.....	E
June 4	28	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	24	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	20	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	16	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	12	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	8	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	4	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	10	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	8	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	6	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	4	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	2	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	1	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	0.5	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	Dir.	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
June 5	28	.....	.....	.....	.....	.....	.....	.....	.....	3.49	.....	6.63
	24	.....	3.04	3.07	2.50	2.24	2.18	1.82	1.12	3.38	6.07	6.46
	20	1.97	2.85	2.88	2.37	2.08	2.00	1.77	1.12	3.27	5.70	6.23
	16	1.67	2.66	2.66	2.19	1.92	1.90	1.71	1.10	3.07	5.45	5.96
	12	1.48	2.42	2.42	1.96	1.62	1.71	1.59	0.96	2.94	.....	.....
	8	1.35	2.21	2.03	1.58	.....	1.50	1.45	0.89	2.60	4.22	4.65
	4	1.10	1.87	1.72	1.46	1.12	1.29	1.15	0.86	3.09	5.24	5.74
	10	1.51	2.40	2.45	1.93	1.59	1.71	1.61	0.86	2.85	4.98	5.46
	8	1.35	2.23	2.18	1.74	1.46	1.53	1.41	0.88	2.78	4.68	5.12
	6	1.34	2.14	2.13	1.67	1.45	1.51	1.40	0.94	2.55	4.24	4.60
	4	1.14	1.93	1.85	1.46	1.24	1.32	1.19	0.89	2.00	3.38	3.61
	2	0.80	1.54	1.17	0.96	0.73	0.75	0.82	0.70	1.56	2.55	2.69
	1	0.65	1.12	0.83	0.75	0.62	0.62	0.73	0.65	0.73	1.55	1.71
	0.5	.....	0.67	0.62	.....	.....	.....	.....	.....	N	N	NE
	Dir.	NE	NE	NE	NE	N	N	N	N	.....	.....	.....
June 6	28	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	2.92
	24	.....	.....	.....	.....	.....	.....	1.01	0.94	.....	.....	2.72
	20	.....	.....	.....	.....	.....	.....	1.01	1.01	.....	.....	2.65
	16	.....	.....	.....	.....	.....	.....	0.91	0.98	.....	.....	2.54
	12	.....	.....	.....	.....	.....	.....	0.82	0.85	.....	.....	2.44
	8	.....	.....	.....	.....	.....	.....	0.76	0.88	.....	.....	2.13
	4	.....	.....	.....	.....	.....	.....	0.65	0.82	.....	.....	2.66
	10	.....	.....	.....	.....	.....	.....	0.75	0.72	.....	.....	2.55
	8	.....	.....	.....	.....	.....	.....	0.75	0.80	.....	.....	2.45
	6	.....	.....	.....	.....	.....	.....	0.73	0.88	.....	.....	2.31
	4	.....	.....	.....	.....	.....	.....	0.65	0.87	.....	.....	1.88
	2	.....	.....	.....	.....	.....	.....	.....	0.70	.....	.....	1.45
	1	.....	.....	.....	.....	.....	.....	.....	0.67	.....	.....	0.61
	0.5	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	SE
	Dir.	.....	.....	.....	.....	.....	.....	S	S	.....	.....	.....
June 9	28	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	24	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	20	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	16	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	12	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	8	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	4	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	10	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	8	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	6	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	4	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	2	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....

Continued

for hours ending at

Noon	13	14	15	16	17	18	19	20	21	22	23	24
.....	6.05	5.48	6.79	5.77	6.48	6.48	4.53	3.89	3.56	3.20	2.21	4.52
.....	5.82	5.25	6.49	5.53	6.17	6.17	4.24	3.58	3.25	2.81	2.03	4.16
.....	5.37	4.91	5.97	5.12	5.66	5.61	3.79	3.06	2.71	-2.34	1.76	3.67
.....	4.77	4.39	5.24	4.50	4.88	4.93	3.15	2.50	1.89	1.64	1.35	2.99
.....	4.42	4.00	4.81	4.13	4.47	4.32	2.88	2.24	1.80	1.41	1.27	2.66
.....	E	E	E	E	E	E	E	E	E	E	E	E
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
7.00	7.25	8.00	8.39	8.23	8.15	8.85	6.77	4.83	4.06	4.24	2.14	2.14
6.89	7.14	7.89	8.31	8.15	7.98	8.70	6.58	4.72	3.94	4.15	2.07	2.07
6.68	6.90	7.69	8.12	7.98	7.77	8.51	6.13	4.62	3.77	4.03	1.97	1.95
6.42	6.59	7.31	7.74	7.56	7.25	7.97	6.01	4.34	3.56	3.82	1.77	1.85
6.01	6.05	6.69	7.21	6.78	6.68	6.95	5.50	3.98	3.15	3.64	1.62	1.66
5.22	5.30	5.79	6.15	5.94	5.76	6.33	4.70	3.35	2.63	2.90	1.30	1.38
6.22	6.37	7.10	7.30	7.28	7.46	8.29	6.12	4.19	3.22	3.63	1.74	1.72
6.02	6.18	6.85	7.00	6.99	7.12	7.92	5.86	4.03	3.09	3.43	1.67	1.68
5.74	5.84	6.48	6.64	6.59	5.01	7.09	5.51	3.77	2.88	3.30	1.66	1.63
5.21	5.27	5.86	5.92	5.94	6.08	6.35	4.99	3.35	2.50	2.91	1.43	1.43
4.21	4.27	4.72	4.78	4.75	4.81	4.90	3.95	2.63	1.98	2.19	0.85	0.77
3.04	3.02	3.37	3.59	3.37	3.35	3.27	2.73	1.85	1.25	1.56	.....	0.72
1.43	1.51	1.89	1.76	1.76	1.90	2.00	1.41	0.93	0.62	0.68	.....	.....
S	S	S	S	N	N	N	N	N	N	N	N	N
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
5.99	5.81	.....	.....	5.50	6.33	6.30	6.74	6.13	4.96	2.68	1.40	2.34
5.84	5.65	.....	.....	5.37	6.15	6.13	6.51	5.84	4.77	2.40	1.29	1.74
5.63	5.50	.....	.....	5.20	5.92	5.89	6.22	5.51	4.50	2.16	1.25	1.69
5.35	5.25	.....	.....	4.72	5.63	5.60	5.84	5.06	4.06	1.88	1.14	1.64
4.53	4.44	.....	.....	3.70	4.58	.....	.....	.....	2.50	1.45	1.17	1.55
4.26	4.29	.....	.....	3.95	4.39	4.36	4.37	3.49	2.21	1.20	1.12	1.38
5.29	5.15	.....	.....	4.86	5.43	5.55	5.60	4.72	3.79	1.74	1.01	1.59
5.04	4.93	.....	.....	4.67	5.14	5.29	5.30	4.36	3.33	1.51	1.14	1.56
4.75	4.67	.....	.....	4.37	4.81	4.94	4.94	.....	2.88	1.45	1.25	1.59
4.34	4.24	.....	.....	4.00	4.34	4.45	4.39	3.42	2.26	1.29	1.14	1.43
3.42	3.40	.....	.....	3.22	3.43	3.51	3.38	2.59	1.38	0.77	0.68	0.82
2.63	2.65	.....	.....	2.52	2.68	2.65	2.65	1.97	0.99	0.65	.....	0.62
1.48	1.45	.....	.....	1.45	1.45	1.34	1.20	0.80	.....	.....	.....	.....
N	NE	.....	.....	NE	NE	NE	NE	NE	NE	NE	NE	NE
.....	.....	4.73	3.68	4.34	6.22	5.35	4.41	2.57	.....	.....	1.98	1.88
3.95	4.39	4.63	3.57	4.23	6.05	5.28	4.29	2.42	.....	.....	1.62	1.82
3.77	4.36	4.53	3.49	4.11	5.90	5.17	4.16	2.35	.....	.....	1.30	1.74
3.74	4.26	.....	.....	4.05	5.71	4.99	4.03	1.92	.....	.....	1.10	1.56
3.54	4.11	4.31	3.31	3.88	5.50	4.77	3.79	2.05	.....	.....	0.93	1.22
3.38	3.85	3.89	3.01	3.26	.....	4.34	3.30	1.67	.....	.....	0.82	1.09
2.88	3.42	3.51	2.76	3.14	4.29	3.66	2.78	1.34	.....	.....	0.65	0.71
3.75	3.85	4.27	3.19	3.78	5.20	4.47	3.54	2.02	.....	.....	0.73	1.13
3.63	3.74	4.20	.....	3.72	5.07	4.35	3.40	1.95	.....	.....	0.77	1.12
3.50	3.59	4.16	3.02	3.51	4.73	4.00	3.11	1.76	.....	.....	0.73	1.03
3.25	3.32	3.68	2.86	3.23	4.26	3.41	2.73	1.56	.....	.....	0.65	0.82
2.63	2.68	2.92	2.28	2.58	3.32	2.76	2.00	0.86	.....	.....	.....	.....
1.88	2.00	2.14	1.79	1.90	2.38	1.98	1.34	0.62	.....	.....	.....	.....
0.74	0.73	0.80	0.78	0.65	0.72	0.64	0.63	.....	.....	.....	.....	.....
S	S	S	S	S	S	S	S	N	.....	.....	NE	NE
.....	.....	.....	.....	.....	8.15	7.33	7.44	6.35	5.94	3.64	.....	.....
.....	.....	.....	.....	.....	7.98	7.10	7.13	6.11	5.68	2.43	.....	.....
.....	.....	.....	.....	.....	7.77	6.82	6.90	5.80	5.45	3.22	.....	.....
.....	.....	.....	.....	.....	7.43	6.43	6.51	5.38	5.06	.....	.....	.....
.....	.....	.....	.....	.....	6.93	5.80	6.10	4.89	4.68	2.45	.....	.....
.....	.....	.....	.....	.....	6.33	5.25	5.38	4.16	4.01	1.85	.....	.....
.....	.....	.....	.....	.....	5.07	4.16	4.19	3.23	3.06	1.35	.....	.....
.....	.....	.....	.....	.....	6.72	5.69	5.80	4.45	4.57	2.12	.....	.....
.....	.....	.....	.....	.....	6.31	5.30	5.40	4.08	4.27	1.93	.....	.....
.....	.....	.....	.....	.....	5.84	4.82	4.96	3.70	3.85	1.66	.....	.....
.....	.....	.....	.....	.....	5.06	4.16	4.30	3.15	3.28	1.25	.....	.....
.....	.....	.....	.....	.....	4.01	3.20	3.31	2.29	2.40	0.73	.....	.....

Table 1--

Date	Ht, obs'r ft	Average velocity										
		01	02	03	04	05	06	07	08	09	10	11
1942												
June 9	1	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	0.5	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	Dir.	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
June 10	28	5.46	5.77	5.55	3.56	2.75	3.58	2.71	4.58	6.71	8.24	.....
	24	5.27	5.49	5.40	3.35	2.57	3.46	2.57	4.42	6.49	8.03	.....
	20	4.96	5.12	5.06	3.20	2.39	3.32	2.39	4.26	6.27	7.85	.....
	16	4.50	4.65	4.60	3.86	2.03	3.06	2.16	4.05	5.94	7.69	.....
	12	4.01	4.16	4.11	2.54	1.67	2.78	1.92	3.79	5.63	7.15	.....
	8	3.30	3.48	3.43	2.07	1.34	2.34	1.64	3.37	5.04	6.43	.....
	4	2.45	2.57	2.66	1.40	0.82	1.59	1.14	2.71	4.08	5.29	.....
	10	3.75	3.93	3.89	2.34	1.43	2.54	1.66	3.61	5.46	7.00	.....
	8	3.37	3.59	3.59	2.13	1.30	2.28	1.53	3.38	5.15	6.66	.....
	6	2.99	3.20	3.25	1.85	1.19	1.98	1.41	3.15	4.70	6.13	.....
	4	2.32	2.66	2.71	1.46	0.80	1.51	1.17	2.71	4.11	5.37	.....
	2	1.77	1.92	1.98	0.98	0.63	0.80	0.91	1.98	3.15	4.13	.....
	1	1.19	1.34	1.32	0.73	.....	0.65	0.68	1.41	2.21	2.91	.....
	0.5	.....	.....	.....	.....	.....	.....	.....	.....	.....	1.40	.....
	Dir.	SE	SE	SE	SE	SE	SE	SE	SE	SE	SE	.....
June 20	28	2.03	1.04	2.05	1.43	2.05	2.18	1.09	2.59	2.65	3.85	5.51
	24	.....	.....	.....	.....	.....	.....	.....	.....	.....	3.63	5.20
	20	1.83	1.15	1.77	1.35	1.83	2.00	.....	.....	2.44	3.59	.....
	16	1.61	1.04	1.59	1.30	1.66	1.80	1.01	2.37	2.34	3.49	4.94
	12	1.46	0.99	1.50	1.20	1.46	1.67	0.97	2.29	2.24	3.32	4.75
	8	1.32	0.91	1.38	1.22	1.24	1.46	0.97	1.93	2.02	3.06	4.01
	4	0.89	0.70	0.88	0.83	0.89	1.10	0.82	1.67	1.71	2.55	3.75
	10	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	8	1.27	0.70	1.27	1.15	1.10	1.34	0.94	2.03	2.02	3.09	4.29
	6	1.15	0.80	1.25	1.12	1.10	1.27	0.73	1.93	1.97	2.97	4.08
	4	0.82	0.70	0.89	0.86	0.89	1.07	0.83	1.71	1.76	2.70	3.76
	2	0.62	.....	.....	0.62	0.68	0.77	0.67	1.12	1.22	1.93	2.81
	1	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	0.5	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	Dir.	N	N	N	N	N	N	NE	SE	S	SW	SW
June 21	28	7.26	5.32	6.08	3.95	3.92	5.09	8.13	9.95	10.82	12.10	10.92
	24	6.84	4.94	5.50	.....	3.79	4.73	7.90	9.54	10.26	11.27	9.94
	20	.....	4.86	5.32	.....	.....	.....	.....	.....	.....	.....	9.76
	16	6.33	4.62	5.06	3.12	3.40	4.27	7.33	8.99	9.66	10.90	9.56
	12	5.99	4.32	4.72	2.90	3.15	3.92	6.95	8.54	9.13	9.68	.....
	8	.....	3.82	4.11	2.49	2.44	2.08	.....	7.87	8.29	9.25	8.33
	4	4.37	2.97	3.17	1.83	2.05	2.54	5.14	6.51	6.49	7.71	.....
	10	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	8	5.58	3.92	4.32	2.57	2.75	3.50	5.94	7.35	8.48	9.94	8.97
	6	5.17	3.56	3.90	2.32	2.47	3.18	5.50	6.87	7.97	9.38	8.46
	4	4.52	3.04	3.38	1.97	2.07	2.65	4.78	6.12	7.08	8.56	7.64
	2	3.06	2.11	2.34	1.22	1.17	1.59	3.56	4.55	5.30	6.23	5.76
	1	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	0.5	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	Dir.	SE	S	SE	SE	S	S	W	W	W	N	N
June 24	28	.....	1.67	1.71	2.44	2.26	1.74	2.80	4.00	7.13	7.25	7.16
	24	.....	1.45	.....	2.13	.....	.....	.....	.....	6.80	7.00	6.84
	20	.....	1.35	1.64	2.05	1.87	1.61	2.47	3.72	6.69	6.90	6.80
	16	.....	1.22	1.61	1.85	1.69	1.51	2.19	3.59	6.48	6.64	6.51
	12	.....	.....	1.51	1.61	1.53	1.43	1.92	3.01	6.08	6.33	.....
	8	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	4	.....	0.68	0.91	0.86	0.99	0.96	1.14	2.46	4.60	4.88	4.77
	10	.....	.....	.....	.....	.....	.....	1.76	3.37	6.20	6.32	6.15
	8	.....	1.04	1.38	1.24	1.46	1.40	1.72	3.32	5.96	6.12	5.91
	6	.....	0.93	1.22	1.09	1.41	1.24	1.51	3.12	5.63	5.74	5.56
	4	.....	0.77	0.94	0.93	1.15	1.15	1.22	2.85	5.12	5.22	5.03
	2	.....	0.65	0.65	0.65	0.68	0.63	0.82	1.97	3.58	3.75	3.70
	1	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	0.5	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	Dir.	.....	S	W	W	W	W	SE	N	N	NW	NW

Continued

for hours ending at

Noon	13	14	15	16	17	18	19	20	21	22	23	24
.....	.....	.....	.....	.....	2.28	2.35	2.37	1.55	1.80	0.63	.....	.....
.....	.....	.....	.....	.....	1.38	0.83	0.72	0.75	0.63	.....	.....	.....
.....	.....	.....	.....	.....	SE	SE	SE	SE	SE	SE	.....	.....
.....	.....	.....	.....	.....	8.15	7.33	7.44	6.35	5.94	3.64	.....	.....
7.00	7.25	8.00	.....	.....	7.98	7.10	7.13	6.11	5.68	3.43	.....	.....
6.89	7.14	7.89	.....	.....	7.77	6.82	6.90	5.80	5.45	3.22	.....	.....
6.68	6.90	7.69	.....	.....	7.43	6.43	6.51	5.38	5.06	.....	.....	.....
6.42	6.59	7.31	.....	.....	6.93	5.80	6.10	4.89	4.68	2.45	.....	.....
6.01	6.05	6.69	.....	.....	6.33	5.25	5.38	4.16	4.01	1.85	.....	.....
5.22	5.30	5.79	.....	.....	5.07	4.16	4.19	3.23	3.06	1.35	.....	.....
6.22	6.37	7.10	.....	.....	6.72	5.69	5.80	4.45	4.57	2.12	.....	.....
6.02	6.18	6.85	.....	.....	6.31	5.30	5.40	4.08	4.27	1.93	.....	.....
5.74	5.84	6.46	.....	.....	5.84	4.82	4.96	3.70	3.85	1.66	.....	.....
5.21	5.27	5.86	.....	.....	5.06	4.16	4.30	3.15	3.28	1.25	.....	.....
4.21	4.27	4.72	.....	.....	4.01	3.20	3.31	2.29	2.40	0.73	.....	.....
3.04	3.02	3.37	.....	.....	2.28	2.35	2.37	1.55	1.80	0.63	.....	.....
.....	.....	.....	.....	.....	1.38	0.83	0.72	0.75	0.63	.....	.....	.....
S	S	N	.....	.....	SE	SE	SE	SE	SE	SE	.....	.....
5.96	5.17	5.65	6.64	8.58	11.35	12.89	11.33	9.80	8.49	7.43	10.45	9.59
5.66	4.96	5.49	6.32	8.36	.....	12.32	10.79	9.49	8.03	6.99	10.02	9.25
4.65	.....	5.41	6.27	8.18	11.16	11.99	10.46	9.20	7.72	6.71	9.08	9.00
5.37	4.81	5.24	5.99	7.87	10.36	11.50	10.07	8.80	7.35	6.32	9.32	8.64
4.91	.....	4.42	5.74	7.51	9.84	10.89	9.48	8.33	6.85	5.94	8.67	8.15
4.53	4.15	4.32	5.01	6.64	8.49	9.53	7.80	6.12	5.79	5.15	7.97	7.46
4.06	3.72	4.03	4.53	5.82	7.40	8.23	6.94	6.07	4.81	4.06	6.35	6.17
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
4.73	4.19	4.72	5.39	6.85	9.15	10.17	8.82	7.64	6.35	5.40	8.05	7.62
4.47	4.00	4.42	5.03	6.33	8.44	9.33	8.15	7.00	5.77	4.86	7.38	7.05
4.00	3.51	3.92	4.32	5.40	7.26	7.95	6.99	5.94	4.84	4.13	6.33	6.13
3.01	2.55	2.80	3.23	4.00	4.96	7.13	4.58	4.00	3.35	2.97	4.65	4.15
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
S	S	S	S	S	S	S	S	S	S	S	S	S
9.84	9.18	6.85	5.61	6.07	7.85	5.99	5.15	4.63	.....	.....	.....	.....
9.37	9.05	6.61	5.35	5.79	7.35	5.71	5.12	4.62	.....	.....	.....	.....
.....	8.92	6.54	5.34	5.66	7.26	5.68	5.01	4.55	.....	.....	.....	.....
.....	8.49	6.30	5.12	5.51	6.95	5.48	4.81	4.24	.....	.....	.....	.....
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
8.07	7.51	5.55	.....	4.73	5.18	4.03	3.89	3.51	.....	.....	.....	.....
6.48	6.13	4.67	3.79	4.06	4.99	3.95	3.42	2.99	.....	.....	.....	.....
8.64	7.92	5.63	4.55	4.84	6.66	5.20	.....	3.70	.....	.....	.....	.....
8.31	7.64	5.50	4.50	4.88	6.43	5.12	4.44	.....	.....	.....	.....	.....
7.88	7.23	5.22	4.24	4.63	6.12	4.84	4.15	.....	.....	.....	.....	.....
7.13	6.43	4.73	3.79	4.16	5.39	4.39	3.72	.....	.....	.....	.....	.....
5.25	4.72	3.53	2.81	3.02	3.91	3.09	2.42	.....	.....	.....	.....	.....
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
N	N	N	NW	W	N	N	N	N	.....	.....	.....	.....
6.87	8.90	8.10	8.92	10.12	10.12	5.96	5.79	4.99	3.22	2.45	2.71	2.26
6.51	.....	7.72	8.46	9.36	9.59	5.87	5.60	.....	3.01	2.19	2.48	2.03
6.40	8.23	7.66	8.35	9.33	9.49	5.87	5.48	4.72	2.96	2.05	.....	.....
6.20	8.05	7.45	8.07	9.20	9.18	5.66	5.27	4.50	2.80	1.90	2.23	1.82
.....	.....	.....	.....	.....	.....	.....	.....	.....	2.55	1.71	2.00	1.61
5.29	6.49	6.37	7.02	7.77	8.00	4.84	4.36	3.89	2.28	1.29	.....	.....
4.60	5.86	5.51	5.86	6.38	6.66	4.01	3.85	3.12	1.56	0.73	0.96	0.68
5.79	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	1.17
5.51	7.11	6.59	7.16	8.13	8.18	5.08	4.62	3.89	2.11	1.24	1.61	1.10
5.39	6.77	6.28	6.73	7.66	7.71	4.77	4.34	3.63	1.93	1.15	1.40	0.98
4.68	6.15	5.65	5.99	7.16	6.49	4.32	3.90	3.22	1.53	0.86	1.12	0.78
3.48	4.50	5.19	3.49	5.04	5.12	3.01	2.78	2.26	0.77	.....	0.67	0.62
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
SW	N	N	NW	NW	N	N	N	W	W	W	SW	S

Table 1--

Date	Ht. obs'r ft	Average velocity 01	02	03	04	05	06	07	08	09	10	11
1942												
June 25	28	1.72	1.66	2.44	2.19	1.97	1.41	0.89	0.67	1.03	.....	3.95
	24	.....	.....	2.19	.....	.....	.....	.....	.....	1.04	.....	.....
	20	1.55	1.61	2.16	2.18	1.74	1.20	0.94	0.70	1.40	.....	3.80
	16	1.46	1.43	1.98	1.87	1.45	0.89	0.75	0.63	1.09	.....	3.67
	12	1.29	1.19	1.74	1.61	1.24	0.80	0.70	0.60	1.12	.....	3.58
	8	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	4	0.83	0.91	1.17	0.80	0.62	0.67	0.65	0.63	0.93	.....	2.90
	10	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	8	1.00	1.12	1.59	1.38	0.88	0.72	0.68	0.63	0.88	.....	3.30
	6	0.99	1.09	1.46	1.15	0.78	0.93	0.68	0.67	0.94	.....	3.17
	4	0.82	0.94	1.27	0.93	0.65	0.67	0.67	0.63	0.99	.....	2.94
	2	.....	.....	0.75	0.62	.....	.....	.....	0.62	0.65	.....	2.14
	1	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	0.5	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	Dir.	S	S	N	N	N	N	N	N	NE	.....	S
June 26	28	3.35	4.85	3.64	2.57	2.97	2.42	2.22	3.09	2.75	2.99	2.47
	24	3.09	4.56	3.40	2.34	2.76	2.24	2.14	2.94	2.66	2.88	2.45
	20	2.85	4.16	3.20	2.13	2.60	2.13	2.08	2.85	2.55	2.81	2.44
	16	2.52	3.79	2.90	1.77	2.40	1.90	1.87	2.68	2.42	2.70	2.34
	12	2.23	3.35	2.55	1.40	2.21	1.69	1.69	2.52	2.26	2.55	2.23
	8	.....	.....	1.88	1.01	.....	.....	.....	.....	1.85	2.38	2.00
	4	1.10	1.87	0.98	0.63	1.19	0.78	0.94	1.56	1.50	1.80	1.61
	10	1.88	2.99	2.16	1.15	1.93	1.35	.....	2.11	1.98	2.39	2.02
	8	1.87	2.85	2.00	1.07	1.92	1.30	1.41	1.90	1.93	2.32	1.97
	6	1.56	2.44	1.55	0.89	1.61	1.12	1.20	1.80	1.72	2.13	1.80
	4	1.32	2.02	1.14	0.65	1.24	0.89	1.03	1.59	1.53	1.92	1.64
	2	0.72	1.27	0.73	0.60	0.67	0.63	0.67	1.01	0.96	1.29	1.01
	1	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	0.5	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	Dir.	NE	NE	NE	NE	NE	NE	NE	NE	N	NE	E
June 27	28	.....	.....	3.17	1.51	2.57	1.74	2.14	3.17	3.40	4.24	5.84
	24	.....	.....	3.04	.....	2.42	.....	.....	3.07	3.23	4.06	5.65
	20	.....	1.88	3.01	1.48	.....	.....	.....	.....	.....	.....	.....
	16	.....	1.64	2.88	1.43	2.35	1.66	2.00	2.90	3.11	3.84	5.29
	12	.....	1.59	2.75	1.34	2.23	1.56	1.92	2.78	2.97	3.67	5.01
	8	.....	1.50	2.49	1.22	1.95	1.41	1.71	2.54	2.71	3.27	4.50
	4	.....	1.10	1.97	0.99	1.50	1.07	1.32	2.00	2.16	2.55	3.59
	10	.....	.....	.....	.....	.....	.....	.....	.....	2.75	.....	4.65
	8	.....	1.51	2.55	1.30	1.98	1.34	1.71	2.49	2.70	3.20	4.52
	6	.....	1.35	2.34	1.22	1.76	1.10	1.50	2.13	2.45	2.85	3.95
	4	.....	1.24	2.13	1.15	1.56	1.04	1.38	1.98	2.21	2.59	3.58
	2	.....	0.75	1.32	0.77	1.03	0.68	0.83	1.30	1.45	1.76	2.49
	1	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	0.5	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	Dir.	.....	S	NE	N	NE	NE	NE	NE	N	NE	NE
July 3	28	.....	.....	.....	.....	.....	.....	.....	.....	6.15	7.74	9.35
	24	.....	.....	.....	.....	.....	.....	.....	.....	5.91	7.52	9.13
	20	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	16	.....	.....	.....	.....	.....	.....	.....	.....	5.51	7.08	8.59
	12	.....	.....	.....	.....	.....	.....	.....	.....	5.12	6.66	8.13
	8	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	4	.....	.....	.....	.....	.....	.....	.....	.....	3.77	5.17	6.49
	10	.....	.....	.....	.....	.....	.....	.....	.....	.....	6.40	7.95
	8	.....	.....	.....	.....	.....	.....	.....	.....	4.73	6.07	7.64
	6	.....	.....	.....	.....	.....	.....	.....	.....	4.32	5.55	7.13
	4	.....	.....	.....	.....	.....	.....	.....	.....	3.90	5.01	6.49
	2	.....	.....	.....	.....	.....	.....	.....	.....	3.17	4.11	5.39
July 4	28	2.05	7.35	8.07	8.31	4.67	5.58	7.11	6.48	6.97	8.48	8.79
	24	1.82	7.10	7.82	8.02	4.46	5.30	6.92	6.27	6.74	8.31	8.64
	20	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	16	1.59	6.40	7.13	7.30	4.01	4.72	6.30	5.77	6.23	7.77	8.13
	12	1.34	6.02	6.64	6.74	3.69	4.29	5.89	5.43	5.82	7.25	7.71
	8	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....

Continued

for hours ending at

Noon	13	14	15	16	17	18	19	20	21	22	23	24
4.70	4.52	6.05	6.27	4.63	3.37	3.74	3.11	1.74	.....	1.93	2.18	1.74
.....	.....	5.86	5.94	4.55	3.28	3.59	2.93	.....	.....	1.77	.....	.....
4.55	4.37	5.76	5.89	4.53	3.23	3.54	2.86	1.69	1.45	1.69	1.93	1.58
4.37	4.27	5.58	5.76	4.24	3.12	3.40	2.75	1.61	1.35	1.45	1.80	1.25
4.21	4.10	5.15	5.46	4.10	2.99	3.12	2.55	1.55	1.27	1.29	1.67	1.11
3.45	3.70	4.79	4.78	3.77	2.70	2.94	2.24	1.40	1.15	1.04	1.48	.....
3.37	3.32	4.16	3.87	3.51	2.34	2.40	1.64	0.96	0.75	0.60	0.98	0.75
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
4.01	3.85	5.01	5.30	3.98	2.86	3.07	2.18	1.30	0.99	1.09	1.48	0.99
3.84	3.62	4.63	4.99	3.70	2.66	2.88	1.88	1.15	1.12	0.88	1.19	0.86
3.53	3.38	4.24	4.57	3.38	2.47	2.63	1.69	0.96	0.83	0.63	1.01	0.75
2.52	2.50	3.11	3.23	2.42	1.65	1.74	1.14	0.65	.....	.....	0.67	0.63
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
N	N	SW	N	N	N	N	NE	NE	E	E	NE	NE
1.43	4.00	4.34	5.51	8.59	5.96	5.71	6.08	4.13	2.80	.....	.....	1.04
1.45	3.89	4.22	5.39	8.44	5.86	5.56	5.96	4.01	2.70	.....	.....	.....
1.48	3.79	4.10	5.25	8.21	5.70	5.50	5.81	3.89	2.55	0.98	1.74	0.93
1.38	3.63	3.90	4.98	7.85	5.46	5.25	5.60	3.72	2.34	0.86	1.59	0.72
1.35	3.43	3.64	4.70	7.36	5.17	4.99	5.32	3.53	2.14	0.65	1.24	0.65
1.15	3.09	2.88	.....	.....	.....	.....	.....	3.06	1.76	0.83	0.89	.....
0.94	2.42	2.50	3.32	5.09	3.69	3.64	3.89	2.42	1.29	0.63	0.63	0.62
1.15	.....	.....	.....	7.00	5.03	4.83	5.14	.....	.....	.....	.....	.....
1.22	3.09	3.22	4.26	6.66	4.91	4.65	4.93	3.17	1.82	0.80	0.96	.....
1.40	2.80	2.88	3.82	6.05	4.50	4.19	4.42	2.81	1.55	0.80	0.78	.....
1.01	2.45	2.54	3.32	5.29	3.89	3.69	3.89	2.44	1.29	0.65	0.65	.....
0.70	1.69	1.67	2.28	3.74	2.68	3.55	2.76	1.51	0.83	.....	.....	.....
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
E	E	SE	SE	SE	S	S	S	S	S	S	S	S
6.99	6.05	4.91	5.70	5.76	5.99	4.84	4.15	3.94	3.23	5.04	1.97	1.12
6.80	5.92	4.81	5.56	5.61	5.84	4.77	4.05	3.79	3.15	4.73	1.76	1.01
.....	.....	.....	.....	.....	.....	.....	.....	3.53	3.07	4.46	1.66	0.94
6.33	5.56	4.60	5.25	5.37	5.45	4.42	3.75	3.30	2.88	4.05	1.48	0.93
6.01	5.30	4.37	5.01	5.15	5.19	4.16	3.53	2.97	2.65	3.58	1.35	0.89
5.48	4.86	4.03	4.60	5.72	4.73	3.64	3.15	2.40	2.05	2.47	1.07	0.96
4.36	3.92	3.32	3.72	3.84	3.84	3.06	2.50	1.59	0.96	1.77	0.73	0.65
5.77	5.03	4.24	4.77	4.83	5.04	4.27	.....	.....	.....	.....	.....	.....
5.50	4.83	4.08	4.58	4.63	4.84	3.82	3.22	2.39	2.11	2.90	1.07	0.88
4.93	.....	3.80	4.22	4.21	4.42	3.46	2.88	1.98	1.64	2.39	0.93	0.89
4.39	3.92	3.40	3.75	3.74	3.90	3.09	2.54	1.59	1.04	1.87	0.78	0.72
3.20	2.86	2.35	2.63	2.59	2.62	2.07	1.53	0.78	0.60	0.70	0.60	0.60
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
E	NE	NE	NE	NE	E	NE	E	E	E	NE	E	E
11.20	.....	13.29	14.82	15.45	14.28	14.49	10.95	14.26	5.04	5.91	5.19	4.78
10.92	.....	12.96	14.49	15.25	14.18	13.37	10.70	13.59	4.88	5.66	4.94	4.55
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
10.28	.....	12.06	13.64	14.20	13.35	12.43	9.57	12.89	4.42	5.03	4.32	4.05
9.72	.....	11.50	12.91	13.39	12.53	11.81	9.35	12.07	4.13	4.58	3.87	3.64
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
7.69	.....	9.06	10.07	10.48	9.72	9.25	7.20	9.26	3.02	3.11	2.52	2.21
9.46	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	3.69	3.32
9.15	.....	10.80	11.86	12.63	11.86	11.20	8.84	11.07	3.70	4.03	3.30	2.94
8.51	.....	10.10	11.05	11.84	11.07	10.46	8.21	9.88	3.18	3.56	2.85	2.52
7.69	.....	9.10	9.92	10.72	10.00	9.40	7.35	9.23	3.01	3.17	2.52	2.23
6.33	.....	7.49	8.13	8.84	8.23	7.47	5.96	7.62	2.40	2.55	1.93	1.62
9.21	8.95	9.16	10.61	9.87	9.08	10.54	.....	5.96	.....	.....	.....	1.25
9.03	8.82	8.85	10.13	9.35	8.27	9.40	8.33	5.77	3.30	2.45	1.24	1.19
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
8.46	8.24	8.33	9.62	8.79	7.98	9.05	7.15	5.35	3.01	2.16	1.10	1.14
8.02	7.82	7.38	7.71	5.27	7.16	8.31	6.58	4.98	2.86	2.00	0.99	1.10
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....

Table 1--

Date	Ht, obs'r ft	Average velocity										
		01	02	03	04	05	06	07	08	09	10	11
1942												
July 4	4	0.80	4.41	4.96	5.08	2.45	2.76	4.34	4.16	4.58	5.81	6.22
	10	.....	5.81	6.48	6.43	3.48	4.01	5.66	5.06	5.66	7.13	7.59
	8	1.07	5.50	6.23	6.18	3.20	3.69	5.43	4.83	5.46	6.92	7.33
	6	0.94	5.01	5.74	5.66	2.78	3.11	4.93	4.37	4.98	6.25	6.84
	4	0.94	4.52	5.22	5.17	2.44	2.71	4.37	4.11	4.60	5.89	6.25
	2	0.72	3.53	4.21	4.13	1.82	2.03	3.58	3.25	3.72	4.84	5.19
July 25	28	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	24	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	20	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	16	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	12	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	8	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	4	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	10	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	8	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	6	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	4	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	2	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	1	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	0.5	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	Dir.	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
July 26	28	.....	.....	.....	.....	.....	.....	2.81	2.81	.....	2.94	4.70
	24	.....	.....	.....	.....	.....	.....	2.78	2.78	.....	2.76	4.63
	20	.....	.....	.....	.....	.....	.....	2.63	2.63	.....	2.85	4.55
	16	.....	.....	.....	.....	.....	.....	2.45	2.45	.....	2.78	4.44
	12	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	4.19
	8	.....	.....	.....	.....	.....	.....	1.83	1.83	.....	2.40	3.94
	4	.....	.....	.....	.....	.....	.....	1.30	1.30	.....	2.19	3.56
	10	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	4.19
	8	.....	.....	.....	.....	.....	.....	1.90	1.90	.....	2.47	4.05
	6	.....	.....	.....	.....	.....	.....	1.71	1.71	.....	2.40	3.92
	4	.....	.....	.....	.....	.....	.....	1.24	1.24	.....	2.32	3.67
	2	.....	.....	.....	.....	.....	.....	1.17	1.17	.....	1.95	3.01
	1	.....	.....	.....	.....	.....	.....	0.88	0.88	.....	1.45	2.37
	0.5	.....	.....	.....	.....	.....	.....	0.60	0.60	.....	.....	1.22
	Dir.	.....	.....	.....	.....	.....	.....	E	E	E	E	SE
1943												
Feb. 20	28	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	24	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	20	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	16	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	12	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	8	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	5	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	4	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	3	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	2	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	1	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Feb. 21	28	4.96	4.31	3.85	1.93	3.69	4.19	1.51	3.02	3.94	5.77	5.96
	24	4.32	3.72	2.94	1.43	3.22	3.77	1.10	1.43	3.40	5.32	5.55
	20	4.32	3.72	3.07	1.80	3.02	3.54	1.24	2.49	2.07	.....	.....
	16	3.85	3.54	2.94	1.51	2.85	3.27	1.24	2.24	3.30	4.86	5.19
	12	2.71	2.24	2.07	1.07	2.21	2.49	1.10	1.88	2.63	3.72	3.90
	8	3.43	3.02	3.52	1.74	2.16	2.49	0.93	1.71	2.66	4.05	4.27
	5	2.63	2.16	1.85	1.32	1.85	2.07	0.88	1.38	2.16	3.58	4.13
	4	2.35	1.88	1.61	1.15	1.10	1.38	0.78	0.88	1.66	2.66	3.63
	3	2.52	2.24	1.85	1.46	1.66	1.93	1.07	1.32	1.89	3.27	3.77
	2	2.07	1.66	1.29	0.93	1.93	0.73	0.65	0.88	1.10	2.85	3.35
	1	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Mar. 11	28	13.19	11.76	7.64	9.10	10.82	10.95	10.63	8.54	6.79	.....	.....
	24	12.98	11.45	7.46	8.82	10.54	10.63	10.41	8.38	6.64	.....	.....
	20	12.48	11.35	.....	8.27	10.08	10.28	10.00	8.10	6.42	.....	.....

Continued

for hours ending at

Noon	13	14	15	16	17	18	19	20	21	22	23	24
6.42	6.15	6.28	7.13	6.48	5.86	6.61	5.20	3.84	2.02	1.35	0.65	0.72
7.72	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
7.54	7.21	7.15	8.17	7.67	7.51	8.41	6.58	4.91	2.70	1.95	1.03	1.07
7.05	6.69	6.69	7.66	7.11	7.05	8.03	6.23	4.55	2.37	1.67	0.78	0.88
6.49	6.05	6.01	6.92	6.58	6.46	7.40	5.71	4.22	2.14	1.51	0.75	0.83
5.37	4.99	5.01	5.76	5.45	5.35	6.22	4.75	3.53	1.62	0.98	0.63	0.63
6.53	7.46	9.08	8.12	8.87	8.48	9.40	8.02	7.87	7.40	6.53	6.92	7.74
6.48	7.40	8.99	8.03	8.79	8.39	9.25	7.92	7.71	7.23	6.33	6.74	7.56
6.38	7.26	8.84	7.88	8.64	8.23	9.06	7.71	7.51	6.90	6.07	6.49	7.28
6.27	7.13	8.62	7.61	8.46	8.03	8.82	7.31	7.23	6.69	5.77	6.18	6.95
6.08	6.94	8.39	7.49	8.24	7.83	8.51	7.21	6.94	6.18	5.40	5.79	6.56
.....	6.64	.....	.....	.....	7.38	7.93	6.74	6.35	5.82	4.84	5.20	6.01
5.24	5.96	7.15	6.38	6.97	6.61	6.97	5.92	5.53	5.01	4.10	4.34	5.12
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
5.76	6.54	7.87	7.23	7.83	7.31	7.87	6.69	6.35	5.81	4.88	5.08	5.94
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	5.50
5.19	5.91	7.04	6.46	7.04	6.51	6.89	5.92	5.51	5.03	4.11	4.32	5.12
4.41	5.04	5.97	5.50	5.99	5.46	5.74	3.66	4.58	4.16	.....	.....	4.19
3.58	3.90	4.60	4.29	4.62	4.31	4.41	3.79	3.48	3.15	2.49	2.57	3.09
2.40	2.80	3.42	3.06	3.46	3.09	3.20	2.59	2.50	2.07	1.64	1.53	2.03
NE	NE	NE	E	E	NE	NE	E	E	E	E	E	E
4.65	4.53	5.04	5.25	6.35	7.52	6.84	6.63	5.92	5.06	3.79	.....	.....
4.62	4.52	5.01	5.17	6.30	7.43	6.79	6.54	5.87	4.99	3.64	.....	.....
4.55	4.39	4.93	5.08	6.18	7.28	6.64	6.40	5.77	4.84	3.43	.....	.....
4.47	4.34	4.84	4.98	6.10	7.13	6.51	6.28	5.63	4.72	3.22	.....	.....
4.34	4.19	4.70	4.86	5.91	6.94	6.32	6.07	5.43	4.52	2.86	.....	.....
4.11	3.90	4.36	4.62	5.60	6.42	5.81	5.60	5.04	4.10	2.37	.....	.....
3.74	3.56	4.01	4.22	4.94	5.81	5.29	5.03	4.43	3.58	1.61	.....	.....
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
4.21	3.98	4.50	4.70	5.70	6.71	6.25	5.81	5.08	4.22	2.63	.....	.....
4.08	3.89	4.34	4.57	5.51	6.42	5.84	5.55	4.88	4.01	2.47	.....	.....
3.82	3.63	4.08	4.31	5.14	5.92	5.43	5.14	4.50	3.69	2.02	.....	.....
3.18	3.01	3.38	3.64	4.22	4.84	4.50	4.21	3.64	2.94	1.30	.....	.....
2.52	2.44	2.68	2.86	3.32	3.84	3.65	3.27	2.81	2.24	0.89	.....	.....
1.34	1.29	1.48	1.74	2.05	2.35	2.26	1.98	1.46	1.03	.....	.....	.....
S	SE	S	W	S	S	S	S	S	S	S	S	S
.....	.....	.....	.....	14.51	14.99	12.35	12.38	10.00	8.27	7.59	4.77	3.90
.....	.....	.....	.....	14.15	14.59	12.02	12.02	9.72	8.00	7.36	4.60	3.43
.....	.....	.....	.....	13.74	14.18	11.72	11.72	9.36	7.72	6.95	4.27	3.40
.....	.....	.....	.....	13.19	13.52	11.18	11.09	8.95	7.28	6.68	3.94	3.07
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
.....	.....	.....	.....	11.58	11.96	9.82	9.67	7.92	6.51	6.05	3.58	2.71
.....	.....	.....	.....	10.54	10.82	8.87	8.74	7.15	5.82	5.46	2.90	1.93
.....	.....	.....	.....	.....	10.22	8.49	8.10	6.82	5.74	5.32	2.51	1.43
.....	.....	.....	.....	9.64	9.82	8.13	7.92	6.56	5.37	4.99	2.85	2.02
.....	.....	.....	.....	8.41	9.00	7.36	6.92	5.96	4.86	4.68	2.39	1.32
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
2.35	4.83	8.87	5.19	4.73	7.87	6.23	5.40	4.55	1.07	2.21	2.63	1.32
1.61	4.41	8.59	4.83	4.05	6.59	5.27	4.41	4.08	.....	1.46	2.16	1.01
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
1.98	4.31	8.18	4.83	4.32	7.36	5.74	4.68	3.63	.....	1.66	2.21	1.07
1.32	3.22	6.81	3.77	3.43	5.82	4.50	3.40	2.66	.....	1.01	1.38	.....
1.10	3.30	7.33	4.50	4.00	6.68	5.19	3.77	3.12	0.82	1.56	1.66	0.88
1.80	3.77	6.79	4.05	3.69	1.56	4.73	2.99	2.02	.....	.....	1.10	.....
1.29	1.88	4.00	3.27	3.07	5.55	3.69	1.85	1.38	.....	0.68	.....	.....
1.88	3.48	6.18	3.94	3.72	5.68	4.31	2.71	2.21	0.96	1.29	1.51	1.07
0.93	2.71	5.63	3.54	3.35	5.14	3.85	2.29	1.71	.....	.....	0.68	0.65
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
4.73	5.09	5.27	5.74	5.74	5.77	7.87	8.18	9.31	11.72	8.64	7.83	12.71
4.05	4.83	5.14	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
4.50	4.73	4.99	5.37	5.32	5.46	7.33	7.69	8.77	10.31	8.18	7.41	12.12

Table 1--

Date	Ht; obs'r ft	Average velocity										
		01	02	03	04	05	06	07	08	09	10	11
1943												
Mar. 11	16	11.94	10.69	6.87	8.13	9.72	9.92	9.64	7.83	6.18	.....	.....
	12	11.53	10.31	6.73	7.83	9.31	9.54	9.36	7.51	6.01	.....	.....
	8	10.49	9.40	6.10	7.23	8.59	8.82	8.58	7.00	5.55	.....	.....
	5	9.40	8.54	.....	6.51	7.92	8.05	7.83	6.46	5.14	.....	.....
	4	8.10	7.87	5.55	6.42	7.72	7.78	7.64	6.28	5.04	.....	.....
	3	7.46	7.64	.....	.....	.....	.....	.....	.....	.....	.....	.....
	2	7.15	6.87	4.77	5.51	6.51	6.68	6.56	5.37	4.36	.....	.....
	1	6.73	6.15	4.08	4.68	5.46	5.63	5.51	4.63	3.72	.....	.....
Mar. 25	28	.....	6.15	7.41	7.56	5.32	1.51	1.98	4.41	6.73	7.92	7.64
	24	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	20	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	16	7.20	5.37	6.37	6.64	4.68	1.38	1.93	3.35	6.15	7.28	7.15
	12	6.79	5.09	6.10	6.37	4.46	.....	.....	3.17	5.91	7.15	6.95
	8	6.15	4.60	5.46	5.82	4.08	1.32	1.74	2.90	5.46	6.68	6.51
	5	5.46	4.08	4.86	5.27	.....	.....	.....	.....	.....	.....	.....
	4	5.24	4.05	4.73	5.19	3.72	.....	1.61	2.49	5.04	6.23	6.10
	3	5.04	3.72	4.31	4.73	3.30	1.19	1.43	.....	.....	5.82	5.63
	2	4.63	3.54	4.19	4.63	3.22	1.15	1.38	2.16	4.60	5.63	5.15
	1	4.00	2.94	3.54	3.82	2.63	0.88	1.15	1.74	3.77	4.73	4.63
Mar. 26	28	2.99	3.82	3.69	4.36	3.90	3.35	.....	.....	3.54	2.90	6.56
	24	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	20	2.66	3.27	3.22	3.94	3.40	2.99	.....	.....	3.22	2.66	6.23
	16	2.35	2.94	2.85	3.72	3.17	2.66	.....	.....	2.94	2.44	6.10
	12	2.21	2.63	2.52	3.30	2.71	.....	.....	.....	.....	.....	.....
	8	1.93	2.11	2.11	2.85	2.39	2.16	.....	.....	2.49	2.21	5.55
	5	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	5.14
	4	1.46	1.61	1.43	2.21	1.66	1.66	.....	.....	2.29	1.93	4.73
	3	1.10	1.38	1.24	1.74	1.61	1.43	.....	.....	1.98	.....	4.83
	2	0.93	.....	0.88	1.51	1.15	0.96	.....	.....	1.51	1.61	4.19
	1	0.68	0.88	0.73	1.01	0.96	0.93	.....	.....	1.43	1.51	4.00
Mar. 27	28	6.10	2.57	4.19	3.69	12.02	14.94	12.35	12.52	8.90	10.44	8.87
	24	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	20	5.82	2.35	3.85	3.40	11.45	14.10	11.76	11.94	8.54	10.08	8.49
	16	5.51	.....	3.54	3.12	10.95	13.52	11.35	11.61	8.27	9.82	8.24
	12	5.27	.....	3.17	2.76	10.58	13.06	10.85	11.21	7.97	9.36	8.00
	8	4.83	1.80	3.07	2.57	9.82	12.07	10.13	10.58	7.56	8.90	7.64
	5	4.08	.....	.....	.....	8.90	.....	.....	.....	.....	.....	.....
	4	3.94	1.29	2.63	2.29	8.74	10.82	9.00	9.54	6.73	8.00	6.82
	3	3.48	.....	.....	.....	8.05	10.05	8.38	9.23	6.56	7.77	6.68
	2	3.35	0.88	2.07	1.71	7.33	9.10	7.69	8.27	5.96	6.95	6.05
	1	3.71	.....	1.80	1.46	6.18	7.83	6.51	7.15	4.99	5.96	5.27

sample. The observations for 31 selected days, between March 18, 1942, and March 27, 1943, are given in Table 1. Some of these observations are presented graphically in Figures 1 to 8.

The diurnal march of wind-structure is well shown in the data for June 10 and July 25 (Figs. 4 and 7). They show that the logarithmic law is valid only during the morning and evening when the thermal structure of the lower atmosphere is adiabatic. From mid-morning until late afternoon when the air is convectively unstable the logarithmic law is not valid. The data do not lie along a straight line when plotted on semilogarithmic paper, but require a line containing concave curvature. During the night, as the air becomes increasingly stable with the development of a thermal inversion, the logarithmic law is likewise invalid. At this time convex curvature develops in the lines fitted to the observations, and becomes greatest in the early morning hours.

In a communication, published seven years ago, Sverdrup [2] pointed out the limitations of the logarithmic law, stating that it is valid only at approximately adiabatic temperature-distribution. He felt that a power law would be required when an inversion is present. Regarding unstable conditions he said: "In the case of strong lapse near the ground the logarithmic law is probably valid up to a height of a few meters above the ground, but above that height convective currents appear

Concluded

for hours ending at

Noon	13	14	15	16	17	18	19	20	21	22	23	24
4.31	4.77	4.86	5.27	5.27	5.27	7.15	7.33	8.41	9.87	7.87	7.10	11.66
4.19	4.63	4.77	5.14	5.09	4.83	6.87	7.05	8.10	9.54	7.59	6.87	11.21
4.05	4.50	4.55	4.91	4.91	4.86	6.42	6.56	7.51	8.87	7.05	6.42	10.41
3.69	4.13	4.32	4.55	4.55	4.46	5.87	5.91	6.82	8.13	6.56	5.77	9.54
3.63	4.05	4.13	4.46	4.46	4.36	5.77	5.87	6.64	8.00	6.32	5.68	9.36
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
3.22	3.58	3.69	3.94	3.90	3.82	4.96	5.04	5.63	2.79	5.37	4.86	7.97
2.76	3.12	3.22	3.43	3.40	3.35	4.31	4.27	4.83	5.74	4.55	4.13	6.79
6.82	.....	8.87	11.53	11.04	.....	10.05	8.49	6.10	3.40	2.66	2.21	4.08
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
.....	.....	8.54	11.09	10.58	9.95	9.67	8.18	5.68	2.99	2.57	2.11	3.69
6.42	.....	8.24	10.69	10.22	9.59	9.28	7.77	5.37	2.63	2.44	2.02	3.40
6.28	.....	8.05	10.36	9.92	9.28	9.05	7.59	5.24	2.24	.....	.....	2.99
5.96	.....	7.15	9.72	9.31	8.77	8.41	7.05	4.86	2.07	2.02	1.88	2.52
.....	.....	6.95	.....	.....	.....	7.72	6.42	4.19	.....	.....	.....	.....
5.40	.....	6.92	9.15	8.87	8.24	7.59	6.15	3.90	1.51	1.51	1.56	1.88
4.99	.....	6.51	8.38	8.00	7.46	7.26	5.87	3.63	.....	.....	.....	.....
4.83	.....	6.15	8.10	7.72	7.36	6.82	5.40	3.35	1.07	1.15	1.15	1.39
4.19	.....	5.24	6.87	6.51	5.68	5.82	4.83	2.99	0.88	0.73	0.78	1.01
8.59	10.05	10.63	13.39	12.48	15.58	15.04	8.90	7.33	10.58	8.13	6.87	5.87
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
8.33	9.72	10.28	13.34	11.89	14.94	14.41	8.49	6.92	10.08	7.77	6.46	5.55
7.92	9.31	9.78	12.30	11.40	14.28	13.69	8.10	6.56	9.59	7.36	6.15	5.24
7.41	8.90	9.40	11.94	10.99	13.83	13.29	7.87	6.32	9.28	7.05	5.91	4.91
7.15	8.38	8.82	11.04	10.13	12.67	12.12	7.20	5.74	8.41	6.37	5.37	4.60
6.51	7.64	8.05	10.05	9.23	11.48	10.95	.....	5.14	6.73	5.63	4.55	3.94
6.05	7.10	7.36	9.31	8.59	10.36	8.69	6.68	4.50	6.56	4.86	4.08	3.63
6.01	7.05	.....	.....	8.46	.....	.....	5.96	.....	.....	.....	.....	3.12
5.40	6.28	6.46	8.24	7.56	9.05	8.24	5.09	3.94	5.77	4.27	.....	3.07
4.91	5.77	5.96	7.56	6.87	8.49	7.97	4.77	3.72	5.46	4.19	3.40	2.99
8.49	9.59	9.87	11.48	13.24	16.29	18.36	16.57	12.35	8.27	8.38	6.15	3.63
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
8.18	9.28	9.51	11.04	12.57	15.58	17.55	15.22	11.66	7.77	7.72	5.60	3.17
7.97	8.95	9.18	10.69	12.22	14.94	16.79	14.99	11.18	7.33	7.33	5.32	2.94
7.69	8.64	8.95	10.22	11.87	14.15	16.08	14.45	10.72	7.05	7.00	5.04	.....
7.28	8.27	8.49	9.82	11.12	13.65	15.18	13.55	9.95	6.46	6.37	4.50	2.57
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
6.51	7.46	7.69	9.00	10.00	12.17	14.15	12.17	8.77	5.46	5.60	4.05	2.11
6.37	7.28	7.41	.....	.....	11.31	12.57	11.18	8.10	5.24	5.09	3.77	2.02
5.74	6.56	6.73	7.83	8.59	10.54	11.72	10.36	7.46	4.68	4.60	.....	.....
4.99	5.77	5.87	6.68	7.41	8.90	9.87	8.74	6.42	4.08	4.05	2.94	1.38

to play a greater part than the ordinary turbulence. These conditions have not yet been sufficiently studied." The data presented in Table 1 show that Sverdrup was correct except for a part of the last statement. When thermal convection is present the logarithmic law is not valid even within a few cm of the ground.

It is evident, therefore, that the equations for turbulent transfer that are derived from Prandtl's theory of fluid turbulence and that assume a logarithmic law of wind-distribution [4] will give values of eddy-diffusivity that are too high under stable conditions that prevail at night and that are too low during the period of convective instability from mid-morning to mid-afternoon.

References

[1] Leonard B. Corwin, A photographic recorder for wind-gradient measurements, Trans. Amer. Geophys. Union, pp. 142-144, 1943.

[2] H. U. Sverdrup, Note on the logarithmic law of wind structure near the ground, R. Met. Soc. (London), Quart. J., v. 62, pp. 461-462, 1936.

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[4] C. W. Thornthwaite and Benjamin Holzman, Measurement of evaporation from land and water surfaces, U. S. Dep. Agric. Tech. Bull. No. 817, 1942.

Soil Conservation Service,
Washington, D. C. (C.W.T.), and New Philadelphia, Ohio (P.K.)

TEMPERATURE-GRADIENT OBSERVATIONS

R. W. Gerdel

In connection with studies of evaporation, which the Soil Conservation Service is conducting, it was found necessary to make a detailed study of the temperature-structure of the lower atmosphere.

In order to achieve the degree of sensitivity required for the study, thermocouple-junctions constructed of No. 30 copper and constantan wire were used. These thermocouples were suspended from a tower at 12 levels between the ground-surface and 24 feet above it. A cross-arm at the top of the tower maintains the thermocouples at a distance of three feet from the iron pipe of which the tower is constructed. Similar thermocouples, of No. 18 copper and constantan wire, have also been inserted in the soil at six levels between the surface and three feet.

The standard reference-junction is attached to the bulb of a calibrated thermometer and inserted into a thermos bottle which is kept in a protected shelter. Temperatures are recorded by the difference between the standard junction and the thermocouples on the tower. This is accomplished by use of a sensitive Leeds and Northrup two-ohm reflecting galvanometer, so adjusted that the movement of the light-beam through a space of one mm on a translucent scale is equivalent to 0°.1F. Temperature-differences of $\pm 14°.0$ may be recorded with the instrument. Where greater ranges in temperature are encountered, one of several supplementary reference-junctions installed at different elevations or buried in the soil may be switched into the circuit.

The tower is located on an old alluvial terrace having a slope in all directions of less than 0.5 per cent. The vegetative cover is old wheat-stubble, well flattened out in the immediate vicinity. The nearest buildings are at least 600 feet distant from the instruments.

Temperature-gradients obtained with this highly sensitive instrument were found to be readily duplicated for any given period under stable atmospheric conditions. The galvanometer rapidly adjusted itself for each thermocouple and the swing of the light-beam after adjustment was slow, uniform, and only a few tenths of a degree. When thermal convection was large, galvanometer-swing often amounted to several degrees, and representative temperature-gradients could be obtained only by use of the averages of several observations at each elevation. Observations were made at each of the various levels in rapid succession, moving according to a fixed schedule upward from the lowest point of observation to the highest. This schedule was repeated a number of times at one-minute intervals. The standard deviations of the means of ten observations taken under stable and unstable conditions at one-minute intervals at the various elevations are plotted in Figure 1. The broken line shows the variation of standard deviation of temperature with height for stable air characterized by a moderately inverted temperature-gradient. The solid line shows the variation with height during a period of excessive thermal convection when there was a superadiabatic lapse-rate. It is generally true that under stable conditions temperature-fluctuations are small and of similar magnitude at all levels while under conditions of thermal instability the temperature-fluctuations are greatest at four feet, diminishing in magnitude at both higher and lower elevations.

It soon became evident that the temperature-fluctuations were highly irregular and of a much shorter period than one minute. In order to obtain more detailed information on their variation with height a great many observations of temperature were made at much shorter time-intervals. Temperature was recorded at several elevations at rates of 40, 60, and 80 per minute for periods of one to six minutes. Current observations are being made at the rate of 40 per minute.

The march of temperature at various elevations for brief periods of time on four different days during the spring of 1943 is shown in Figures 2, 3, 4, and 5. The observations at the different levels were not made simultaneously; thus the maxima and minima and their distribution-patterns are not comparable. The observations of Figure 4 represent most nearly stable conditions and those of Figure 2 the greatest convective instability. Several different cycles varying in

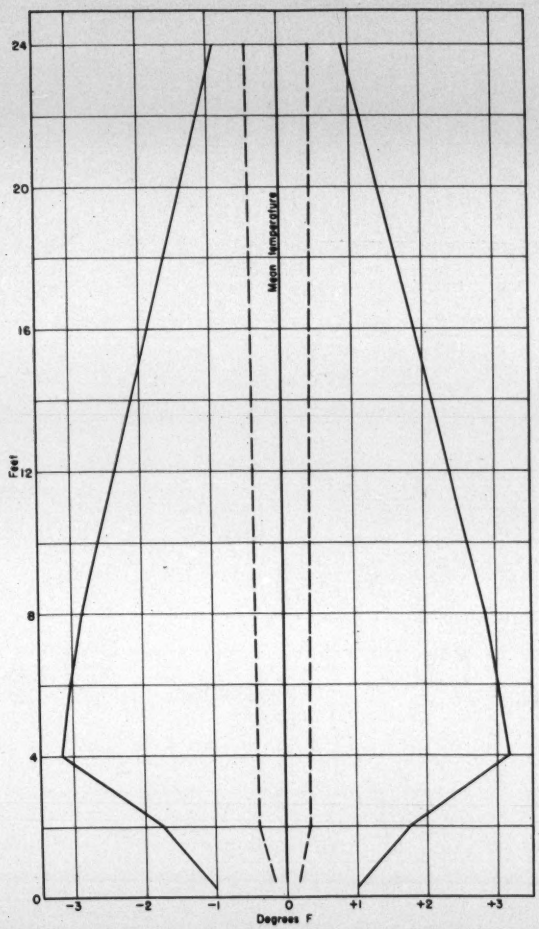

Fig. 1--Fluctuations in temperature at various heights above ground, New Philadelphia, Ohio: Broken line for stable air having an inverted temperature-gradient, 9:00 a.m., March 10, 1943; solid line for unstable air characterized by excessive thermal convection and a super-adiabatic lapse-rate, 1:39 p.m., February 25, 1943

wave-length from a few seconds to several minutes and in amplitude from a few tenths of a degree F to several degrees are revealed. These are superimposed upon the well-known diurnal temperature-cycle, no suggestion of which appears in the brief periods represented.

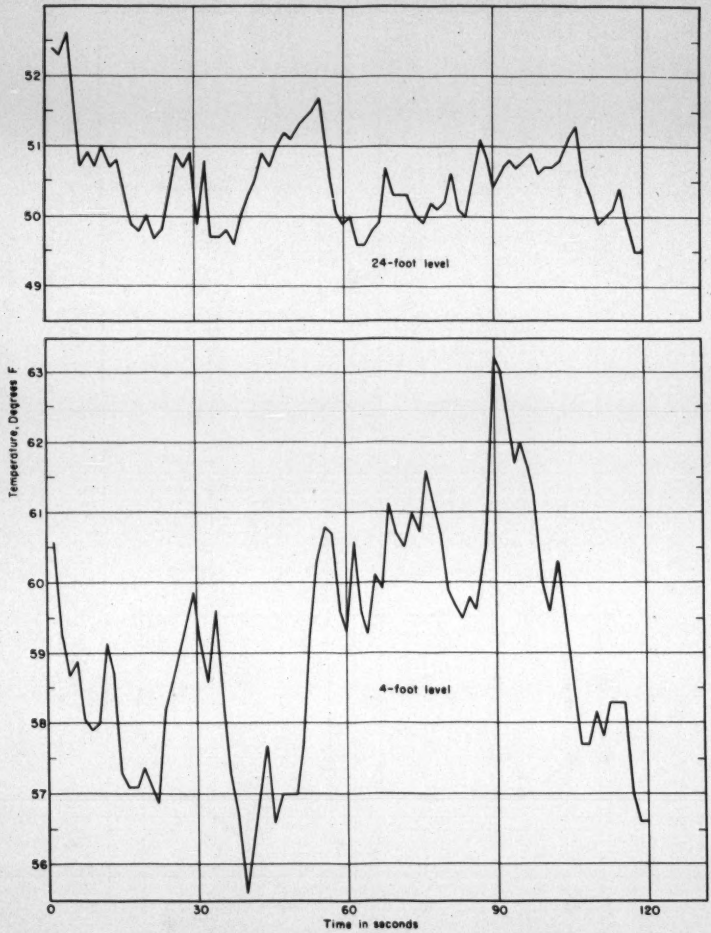

Fig. 2--March of temperature at two levels, New Philadelphia, Ohio, 2:30 p.m., March 27, 1943 (observations were not made simultaneously at the two levels)

Frequency-distribution graphs of these observations are presented in Figures 6, 7, and 8. The patterns for duration and amplitude of change in temperature for May 3 and 4 are almost exactly reversed. Among the observations of May 3 small fluctuations in temperature occurred most frequently at the one-foot level and decreased toward the 24-foot level. Among those of May 4 the small fluctuations in temperature are much less frequent at the one-foot level than at 24

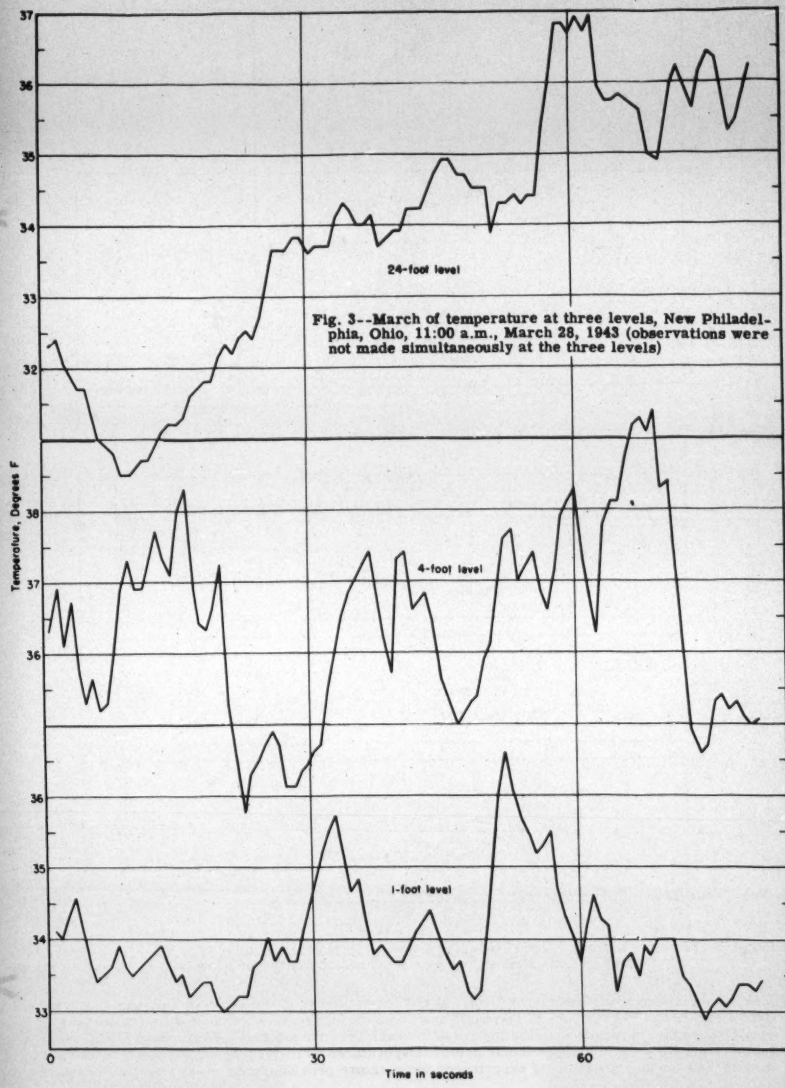

Fig. 3--March of temperature at three levels, New Philadelphia, Ohio, 11:00 a.m., March 28, 1943 (observations were not made simultaneously at the three levels)

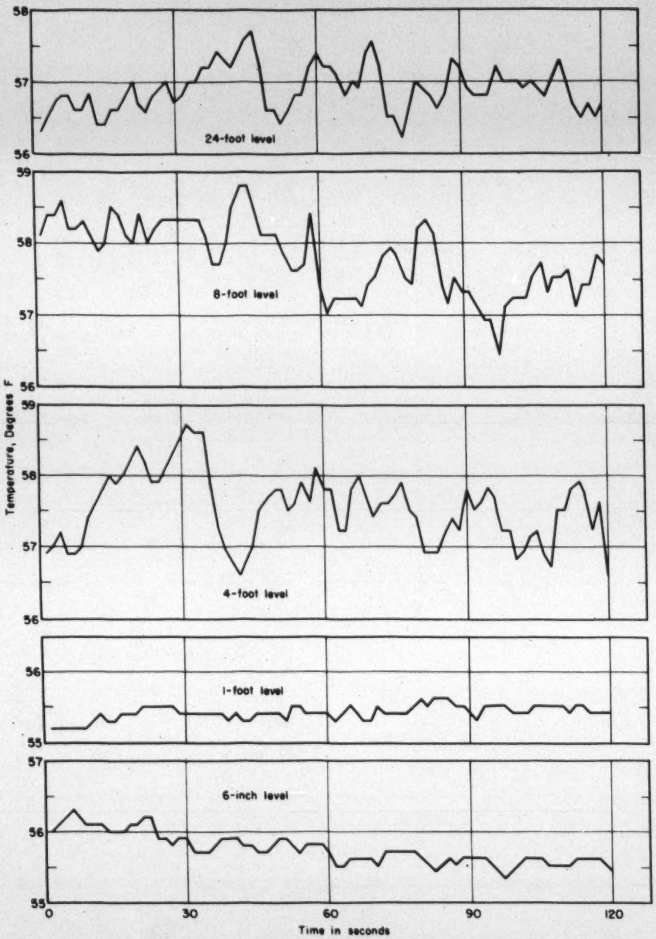

Fig. 4--March of temperature at five levels, New Philadelphia, Ohio, 11:00 a.m., May 3, 1943 (observations were not made simultaneously at the five levels)

feet. The frequency-distributions of experienced temperatures at the one-foot and four-foot levels derived from the observations of March 28 are shown in Figure 9. A value of temperature was recorded on the frequency-distribution graph for each time the plotted line crosses a given temperature-line. For this particular period temperatures were recorded at 80 observations per minute, and the determination of experienced temperature provides many more than the recorded

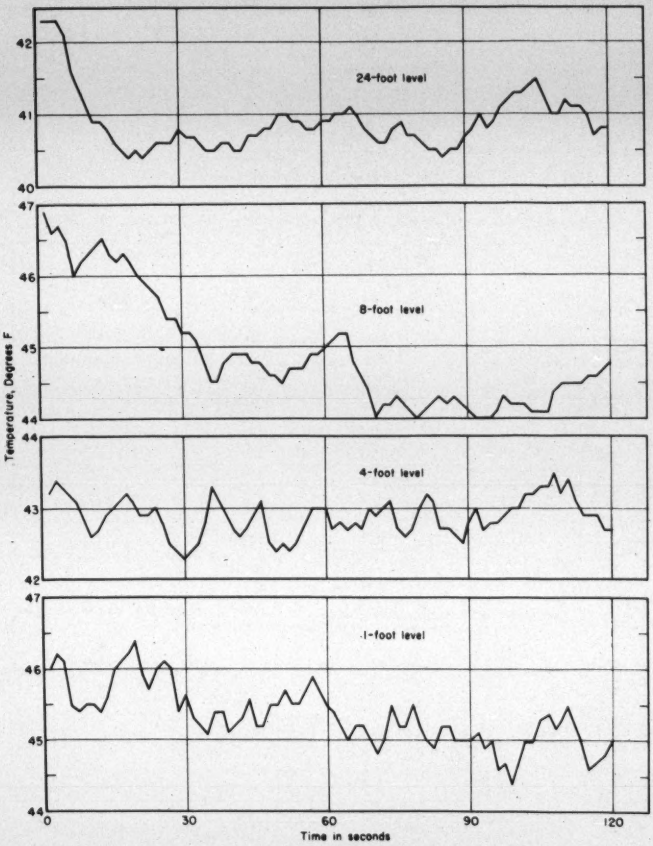

Fig. 5--March of temperature at four levels, New Philadelphia, Ohio, 8:15 a.m., May 4, 1943 (observations were not made simultaneously at the four levels)

number of points for plotting, which results in a continuous curve for the period of observation.

Although the study of the temperature-structure of the layer of air near the ground is only in the initial stage it has been found that temperature fluctuates through several degrees within the space of a few seconds, and that these fluctuations vary in amplitude with height, time of day, and such atmospheric conditions as clear or overcast sky. During periods of high thermal convection when temperature lapse-rates are super-adiabatic, large fluctuations in temperature are greatest between four and eight feet above the ground. The amplitude decreases at both higher and lower elevations.

In the early morning, under clear skies, fluctuations in temperature may be greatest near the

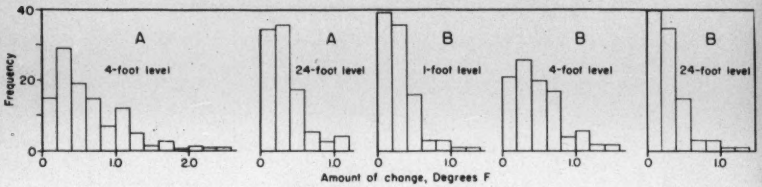

Fig. 6--Frequency of temperature-changes of specified amounts at various levels above ground: (A) Observations of March 27, 1943; (B) observations of March 28, 1943

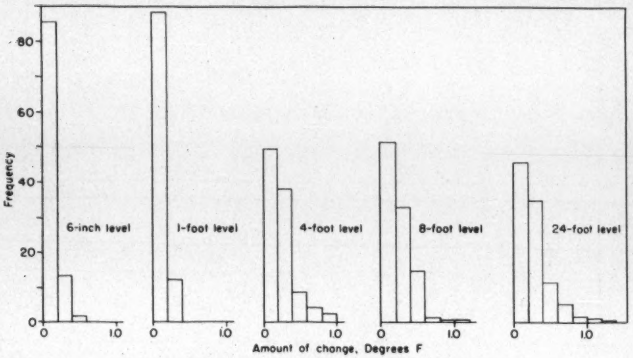

Fig. 7--Frequency of temperature-changes of specified amounts at various levels above ground, observations of May 3, 1943

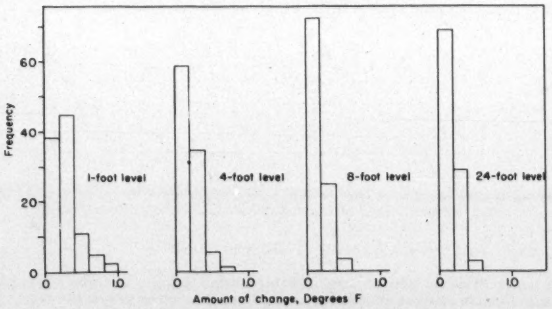

Fig. 8--Frequency of temperature-changes of specified amounts at various levels above ground, observations of May 4, 1943

ground, and least at elevations above eight feet. Under conditions of heavy low overcast, the amplitude of temperature-fluctuations is very small at one foot or less and much larger above four feet. The non-symmetrical frequency-distribution curve obtained for the one-foot elevation, and

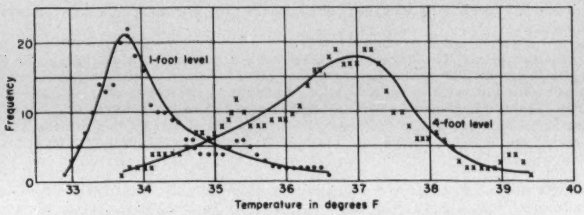

Fig. 9--Frequency-distribution of experienced temperature for the 4- and 24-foot levels, observations of March 28, 1943 (each series represents 80 seconds' elapsed time)

the more nearly symmetrical curve for the four-foot elevation may indicate that under some conditions the ground-surface causes a distortion of the normal turbulence-bodies and interferes with the process of turbulent transfer. Further studies on temperature-gradients and turbulence are in progress.

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ANALYTICAL INTERPRETATION OF DENSITY-CURRENTS OF AIR CHILLED BY NOCTURNAL RADIATION

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The flow of cold air down slopes on clear, calm nights is a familiar phenomenon which is of great significance to citrus growers during radiation frost weather. The current is due to the fact that chilled air is more dense than that unchilled and therefore tends to underrun the lighter air. This phenomenon is somewhat similar to the submerged flow of salt water, or of water with solids in suspension, under clear fresh water. The status of knowledge in those fields is seen in papers such as those by O'Brien and Cherno, by Kalinske, and by Dobbins [see 15, 9, 10, 3 of "References" at end of paper]. The authors have not seen an adequate analytical method which would satisfactorily treat buoyancy-stability and account for the eddy-transfer of heat or moisture across fluid planes of zero shear-stress. It is hoped that critical discussions of this paper will lead to that objective.

The basic cause of nocturnal cold-air drainage is the steady net discharge of heat by radiation from solid surfaces (mainly foliage) to the cold, clear sky. Foliage has very little heat-capacity itself, so exposed leaves quickly become enough colder than the surrounding air to take the required heat from the air. This continual chilling of the air is a factor not found in other types of density-currents. Heat taken steadily from an abnormally slow current of air would cause an extra large degree of chilling; then this chilled air, being extra dense, would tend to flow faster. Conversely, if air flows abnormally fast, the excess air per unit-time coming in contact with the foliage heat-exchanger, will supply the heat-demand for sky-radiation loss with a less-than-normal drop in temperature. This deficient temperature-drop results in less-than-normal difference of density between chilled and unchilled air, and hence the velocity of flow would tend to decrease. It is seen that the degree of chilling (temperature-drop) is inversely related to the air-velocity, but that the force inducing flow is directly related to the degree of chilling. Thus the velocity induced by chilling counters the chilling, and there is an equilibrium-velocity which will change as the net radiation-demand changes. The velocity varies also with the slope of the ground, and with the frictional resistance to flow. The degree of chilling is modified by gaseous radiation and by vertical heat-transfer by means of an eddy-diffusion depending on intensity of turbulence and on thermal gradients.

An understanding of the velocity-profile of a cold-air current is of practical interest to agriculturists, and a satisfactory analysis of it would furnish means for calculating transfer of heat and mass. Hence there is need both for an overall treatment to be applied with due attention to topography and trees, and for a technical analysis to interpret the fluid dynamics of flow under conditions of non-uniform pressure-gradient and buoyancy-stratification. A simplified technical

analysis is presented herein as a necessary preliminary even for interpretation of observations of cold-air drainage.

In view of the extensive literature on turbulence, the major technical difficulties arise from non-similar gradients of velocity, temperature, and vapor-pressure, and from the effect of buoyancy-stratification on internal fluid-friction. In addition, the nature of frictional resistance to flow through orchards is obscure at present and this cannot be treated without a full understanding of density-currents over smooth surfaces. Eventually one should be able to calculate the effect of trees and of change of ground-slope, including the important special case of a level orchard adjacent to a canyon.

Unfortunately, the motivating force of density-currents, namely, the direct chilling of air, occurs not at a smooth surface but within the depth of the foliage which is the region of "rough surface" in the usual treatment of velocity-profiles in fluid flow. Furthermore, with low air-drift velocities, there is stratification which allows the coldest air (having greatest gravitational tendency to flow) to locate near the ground. The force producing cold-air drainage exists within the stream and varies with the degree of chilling of each stratum. Thus the effective pressure stream-line gradient (dP/dx) producing density-flow is not uniformly distributed vertically as an end-push for isothermal flow in pipes, but decreases with height.

The usual fluid-flow treatment [1] is therefore inadequate fundamentally because the simplified Prandtl treatment implies that the pressure stream-line gradient is concentrated at one plane (in spite of wrongly indicating constant shear-stress through the flow-section to the boundary-surface), and because the use of the von Kármán ratio of velocity-derivatives is valid only over a limited range for uniformly distributed pressure stream-line gradient. Furthermore, the buoyancy stratification in density-currents introduces work (thermal potential energy) in the vertical action of eddies. Hence the analysis of density-currents requires a complicated treatment, but preferably one retaining a modified concept of mixing-length if it can be extended to treat the variable forces of shear and buoyancy.

Net pressure stream-line gradient of density-currents.--In nocturnal cold-air drainage, both the density-pressure gradient and the effective barometric pressure-gradient are acting. Here we consider only the component of barometric gradient which is coaxial with the density-current. The rate of change vertically of this effective barometric horizontal pressure-gradient usually is exceedingly small relative to that of density; hence it can be considered constant throughout the depth of density-currents without appreciable error. One cannot, however, neglect this component of the general barometric pressure-gradient because if it is concurrent with the density-pressure gradient, the level of maximum velocity will be far above the density-current proper. This alters the usual concept of density-current as a submerged flow at the bottom of a generally stationary fluid, although velocity of flow near the ground will depend primarily on the density-pressure gradient. In such cases the velocity-profile must be based on decrease in shear-stress from the ground up.

In this study the role of barometric pressure is considered in the more limited, but common, cases of closed thermo-siphon circulation, such as is found in and above a valley due to surface-cooling. In such cases the barometric pressure-component is counter to the density-flow. This is shown diagrammatically in Figure 1, where at the lower limit of adiabatic lapse-rate (upper limit of buoyancy-stratification), line B, it is assumed that there is a barometric pressure-gradient component - $(dP_b/dx) = p_{xb}$ (line A), opposing the density-current. This gradient is plotted also in the coordinate scheme of Figure 1, as the vertical line slightly to the left of the zero-abscissa, indicating negative constant value with height. Within the depth of buoyancy-stratification there is a density-pressure gradient, $p_{x\theta}$, in the direction of flow, due to the difference in temperature between the stably stratified air and the air on the same horizontal level, distant from the chilling surface (in the adiabatic lapse-region above line B). In Figure 1 this is shown as a coordinate curve from the zero-abscissa at the upper limit of buoyancy-stratification down to the sloped ground. The net pressure stream-line gradient (neglecting small inherent dynamic pressure-changes), namely, $(p_{xb} + p_{x\theta}) = [p_{x(b + \theta)}]$, appears in Figure 1 between the two independent gradients. There is thus a height, z_h, at which there is no net pressure-gradient ($p_{x(b + \theta)} = 0$), and consequently no flow of air in the line of density-pressure gradient. Also at the ground, z_0, the flow will of course be zero. Between those two heights there exist strong density stream-line gradients which induce the density-current.

The effectiveness of differences in temperature in creating density-pressure gradients is seen in Figure 1 in relation to a piece of elemental stratum, of thickness Δz and length Δx. At the

Z-axis the pressure on the upstream face is the barometric pressure of the top of the stable stratification, plus the increase within the stratification down to z, amounting to ΔP_{za}. The opposing pressure on the downstream face at a distance Δx from the Z-axis is made up of the same overhead barometric pressure above the isobarometric plane, and the same pressure increase ΔP_{za} within the stable stratification; but in addition there is the counter barometric increment $-\Delta P_b = (p_{xb})\ \Delta x$, and the additional depth of atmosphere (due to sloped ground) of ΔP_{ba} which is equal to the adiabatic density, γ_a, times the vertical depth $\Delta x \sin \phi$, where ϕ is the angle of slope of the ground. Thus externally the force, $F_{xb\Delta x}$, on the downstream face, $\Delta y \Delta z$, of the stratum exceeds the force, F_{xbo}, on the upstream face, by $(-p_{xb} + \gamma_a \sin \phi)\ \Delta x \Delta y \Delta z$. Within the stratum itself there is a force, $F_{x\theta}$, urging flow downhill equal to the weight of the elemental-stratum volume itself, $\gamma_z\ \Delta x \Delta y \Delta z$, times the slope-factor, $\sin \phi$. Therefore the net force inducing flow down slope is $F_{x\theta} + F_{xbo} - F_{xb\Delta x} = \gamma_z \sin \phi\ \Delta x \Delta y \Delta z - (\gamma_a \sin \phi + p_{xb})\ \Delta x \Delta y \Delta z$, and the net stream-line pressure gradient is

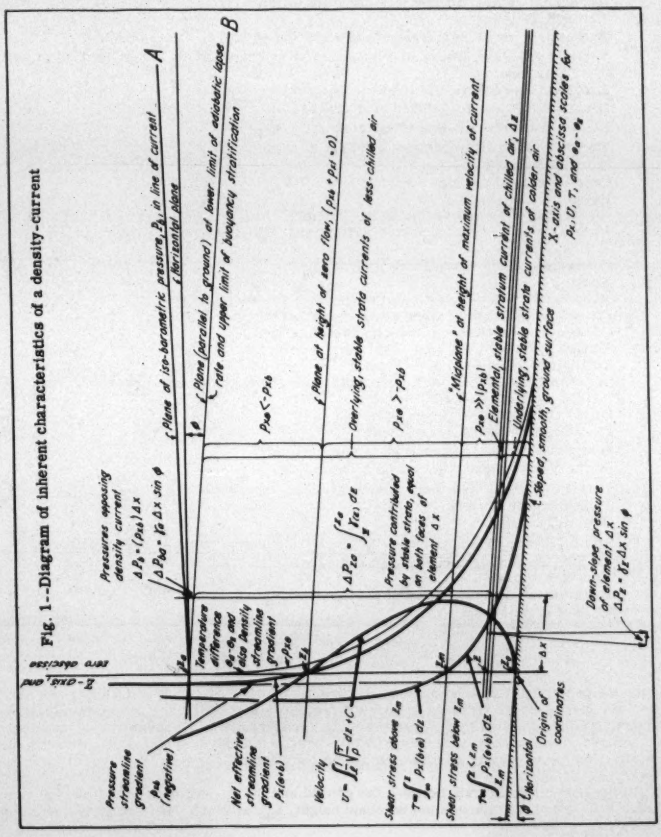
Fig. 1--Diagram of inherent characteristics of a density-current
Z-axis, and zero-pressure
Pressure streamline gradient p_{xa} (negative)
Net effective streamline gradient $p_x(n+i)$
Velocity
Shear stress above z_n
Shear stress below z_n
Pressures opposing density current
Temperature difference $\theta_a - \theta_z$ and also density streamline gradient p_{xa}
Plane of iso-barometric pressure, P_{za}, in line of current
Horizontal plane
Plane (parallel to ground) of lower limit of adiabatic lapse rate and upper limit of buoyancy stratification
A
B
$p_{xa} < p_{xb}$
Plane of height of zero flow, ($p_{xa} = p_{xi} = 0$)
Overlying, stable strata currents of less-chilled air
$p_{xa} > p_{xb}$
Pressure contributed by stable strata, equal on both faces of element Δx
"Mid-plane" of height of maximum velocity of current
$p_{xa} \gg |p_{xb}|$
Elemental, stable stratum current of chilled air, Δz
Underlying, stable strata currents of colder air
Sloped, smooth, ground surface
X-axis and abscissa scales dx
p_x, U, τ, and $\alpha_n - \phi_n$
Down-slope pressure of element Δx
$\Delta P_\phi = \gamma_z \Delta x \sin \phi$
Origin of coordinates
Horizontal
Δx

Table 1--List of symbols used

Symbol	Meaning
a	Lower limit of adiabatic lapse-rate
b	(Subscript) barometric
C	Proportionality-constant in empirical equations
c_p	Specific heat of fluid at constant pressure
E	Rate of energy-dissipation per unit stationary volume
F_{xbo}	Force on upstream side of fluid element
$F_{xb\Delta x}$	Force on downstream side of fluid element
$F_{x\theta}$	Downslope component of weight of fluid element
g	Acceleration of gravity
K	Time-correlation between turbulent velocity-components at a point
ℓ	Mixing-length (Prandtl form)
n	(Subscript) neutral atmosphere (zero-stability)
P_b	Barometric pressure
ΔP_b	Barometric pressure-increment in direction of flow (= - $p_{xb}\,\Delta x$)
ΔP_{za}	Vertical pressure differential between any height z and the lower limit (a) of adiabatic lapse-rate
p_{xb}	Barometric pressure-gradient = - (dP_b/dx)
$p_{x\theta}$	Density-pressure gradient in direction of flow
$p_{x(b+\theta)}$	Net pressure stream-line gradient (= $p_{xb} + p_{x\theta}$)
$p_{xo\theta}$	Intercept of density-pressure gradient at z = 0
Q	Quantity of heat
q	Quantity of heat per unit-time
Re	Reynolds' number
Ri	Richardson's number $(g/\theta)\,(d\theta/dz)/(dU/dz)^2$
Ri'	Alternate form of Richardson's number [Ri' = Ri/(Ri + 1)]
r	Radius of pipe
s	(Subscript) stable atmosphere [$(d\theta/dz) > 0$]
t	Time
U	Mean velocity in x-direction at elevation z above slope
u	Instantaneous velocity along slope in x-direction (u = U + u')
u'	Oscillatory component of velocity in x-direction
V	Volume of fluid
w'	Oscillatory velocity in z-direction
x	Distance along slope [the X-axis runs down slope, the Z-axis is vertical, angle between the axes is $(90 + \phi)°$]
z	Height above slope
z_h	Height of zero pressure-gradient
z_m	Height of zero shear-stress (maximum velocity)
z_o	Height of equivalent plane surface (zero-flow)
β	Exponential coefficient in pressure-gradient expression
γ	Weight density of fluid ($\gamma = \rho g$)
ϵ	Eddy-diffusivity
θ	Potential temperature (absolute scale, adiabatic equivalent at 1000 millibars)
κ	von Kármán mixing-length constant
ρ	Mass-density of fluid
τ	Shear-stress over a horizontal plane
ϕ	Angle of ground-slope

$$[\Delta P_{x(\theta + b)}/\Delta x] = p_{x(\theta + b)} = (\gamma_z - \gamma_a) \sin \phi + p_{xb} \qquad (1)$$

Since the density stream-line gradient is directly proportional to density-difference, and densities are inversely proportional to absolute temperatures (which are large), the density stream-line gradient is directly proportional also to difference in temperature. Thus by appropriate choice of abscissa-scales the temperature-profile may be used to indicate directly the vertical distribution of density stream-line pressure-gradient.

In the density-current strata between the ground and the z_h-height of zero-flow, the rates of flow differ with height, and there must be some height, z_m, at which the velocity is a maximum.

This height can be visualized as analogous to the "midplane" of two-dimensional flow between parallel plates although the velocity-profile above z_m is not a reflection of that below. The significant fact at this height, in comparing outdoor density-currents with closed channel-flow, is that here in both cases the vertical flow-velocity gradient (dU_x/dz) is zero, and the magnitudes of the velocities developed must be those whose frictional losses in shear-stress balance the cumulative pressure-gradient from z_m to the surface.

The region above z_m is difficult to treat because of observational difficulties at a distance from the ground, and because the gradients are small while the variations from the mean values are large. In short, there is no upper solid surface creating a simple reflection-pattern of conditions from "midplane" to ground. Under favorable circumstances the height of zero-velocity can be estimated roughly by extrapolating the density-gradient curve to the height where it would balance the barometric pressure-gradient in the direction of flow. Then by integrating the net pressure stream-line gradient from z_m to z_h one could get some idea of overhead shear-stress and velocity-distribution. Fortunately, most of the important lower region from the ground up to the plane of maximum velocity is directly observable.

Mathematical representation of density stream-line gradient--To treat any set of observations in a consistent manner it is convenient to represent them by an appropriate mathematical expression. It is, of course, desirable to use a function which will lend itself readily to subsequent mathematical operations. However, these subsequent operations have been found so cumbersome for ordinary flow-problems that only simplified expressions are in general use. Hence, for the complicated phenomena of density-currents we shall not attempt to carry any one function through all the mathematical operations needed to obtain an expression for velocity-profile. Instead we shall use two expressions easily fitted to empirical data and then fit another expression to their products. This procedure is a simplified form of step-by-step numerical integration which preserves more truly the characteristics of the observed data than would be possible in using less appropriate functions capable of successive integration.

At a single location one cannot observe the sum of density-pressure gradient and of barometric pressure stream-line gradient. The former is indirectly observable, however, during nocturnal radiation in that the degree of chilling can be deduced relative to the potential temperature above. Usually the difference decreases very rapidly from the surface upward, but tapers off indefinitely at considerable height.

To represent such characteristics the exponential, $p_{x\theta} = p_{x0\theta}\, e^{-\beta z}$ appears most convenient. (If the temperature-profile straightens near the ground, the rectangular hyperbola, $p_{x\theta} = [p_{x0\theta}/(z + \alpha)^n]$, might provide a better fit. This function can be made to yield a finite integral for the upper region, where $p_{x\theta}$ approaches zero as z approaches infinity, by using an exponent slightly less than unity.) This is readily fitted to empirical data by semi-log plotting log $p_{x\theta}$ against z. The intercept at $z = 0$ is $p_{x0\theta}$, and the value of β is found from the slope of the curve paying due attention to equal units of arithmetical scale and of natural logarithm. It is usually quicker to calculate $\beta = 2.3\,[\log_{10}(p_{x0\theta}/p_{x\theta})]/z_{x\theta}$.

The full expression for pressure stream-line gradient is then

$$p_{x(\theta + b)} = p_{x0\theta}\, e^{-\beta z} + p_{xb} \qquad (2)$$

Relation between shear-stress and pressure-gradient--The vertical distribution of shear-stress, τ_z, and of pressure stream-line gradient, $-(dP/dx)_z$, are fundamental to velocity-profiles. In the simplest case of fluid flow between smooth boundary-surfaces and resulting from a pressure-gradient (in the direction of flow) which is uniform over the sectional area of flow, the controlling relation over a given length of stream is well known, namely, that the pressure-loss in line of flow times the sectional area must equal the friction-force exerted by shear-stress over the peripheral stream-boundaries. For uniform pressure-loss over a circular section along an axial distance, x, the net force over the whole section-area is $\pi r^2 x(dP/dx)$. This must equal the tangential shear-stress, τ, at the circular boundary, r, times the peripheral area in the axial distance, that is, equal $2\pi rx\tau$.

In general, the shear-stress at any boundary-surface for uniform pressure-gradient is $\tau = -(dP/dx)$ (section-area/perimeter). For flow in circular pipes (for which experimental data are more complete) the shear-stress at the wall is $\tau_0 = -(r_0/2)(dP/dx)$. For flow between infinite parallel plates separated a distance $2z_m$, the corresponding relation is $\tau_0 = z_m\,(dP/dx)$. It is to be noted that in the above comparison of flow in pipe and semi-infinite channel-flow, r_0,

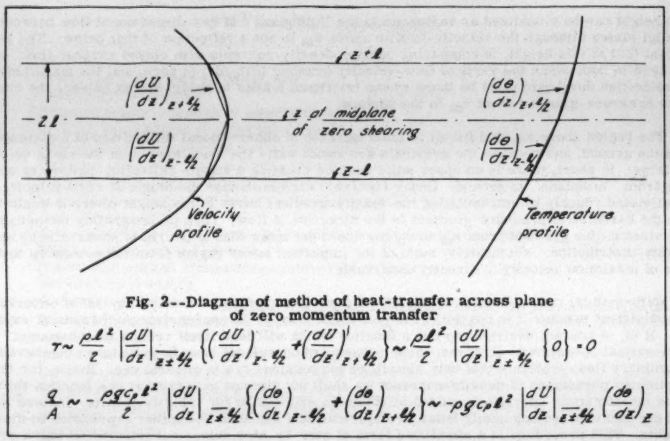

Fig. 2--Diagram of method of heat-transfer across plane of zero momentum transfer

$$\tau \sim \frac{\rho l^2}{l} \left|\frac{dU}{dz}\right|_{z \pm \frac{1}{2}} \left\{\left(\frac{dU}{dz}\right)_{z-\frac{1}{2}} + \left(\frac{dU}{dz}\right)_{z+\frac{1}{2}}\right\} \sim \frac{\rho l^2}{l} \left|\frac{dU}{dz}\right|_{z \pm \frac{1}{2}} \{0\} = 0$$

$$\frac{q}{A} \sim -\frac{\rho g c_p l^2}{l} \left|\frac{dU}{dz}\right|_{z \pm \frac{1}{2}} \left\{\left(\frac{d\theta}{dz}\right)_{z-\frac{1}{2}} + \left(\frac{d\theta}{dz}\right)_{z+\frac{1}{2}}\right\} \sim -\rho g c_p l^2 \left|\frac{dU}{dz}\right|_{z \pm \frac{1}{2}} \left(\frac{d\theta}{dz}\right)_z$$

and z_m are the same distance to or from the boundary-surface from or to the mid-line of zero-shear-stress. Hence, the shear-stress analysis for two-dimensional channel-flow can be applied to pipe flow with only a halving of τ for a given pressure-gradient - (dP/dx).

Figure 1 pictures two-dimensional flow with height z, measured from the solid bottom-surface, z = 0. The midplane, z_m, represents the surface at which there is no net momentum-transfer. This is the plane of zero shear-stress, where there is zero mean-velocity gradient, that is, where (dU/dz) = 0. When there is uniform vertical distribution of pressure-gradient, the shear-stress at any depth (z_m - z) must equal the pressure-gradient times the depth from the zero shear-stress height as in (3a).

$$\tau_z = + p_x (z_m - z) \qquad (3a)$$

where the pressure stream-line gradient, p_x = - (dP/dx), is taken as positive producing the flow and positive shear-stress. This indicates that shear-stress would change even more rapidly with height if, as in density-currents, there is a decrease of pressure-gradient with height. In no real case would shear-stress be invariant. Hence the Prandtl inference [20,21] of shear-stress constant with height is a meaningless by-product of assuming simple logarithmic velocity-distribution which happens to fit fairly well observations of fluid flow in pipes in the region near the surface.

Specifically, the vertical distribution of velocity of a horizontal air-drift above a plane surface (in response to a horizontal pressure-gradient) must be such that the corresponding vertical distribution of friction-head loss in horizontal layers matches the cumulative vertical distribution of pressure stream-line gradient. The friction-force is the shear-stress, and hence if the relations between shear-stress, velocity-gradient, and height are known, the velocity-profile can be determined for a given non-uniform pressure-gradient distribution.

Since the shear-stress (τ_z) at any height must equal the integrated varying pressure stream-line gradient to the flow-section from midplane (z_m) down to height (z), equation (3a) must be generalized for density-currents to

$$\tau_z = \int_z^{z_m} p_{x(\theta + b)}\, dz$$

Then using the semi-exponential expression of equation (2) for the pressure stream-line gradient as a function of height, the shear-stress at any height, z, is

$$\tau_z = (p_{x0\theta}/\beta)\,(e^{-\beta z} - e^{-\beta z_m}) + p_{xb}\,(z_m - z) \qquad (3b)$$

Mixing-length concept relating shear-stress and velocity--The essential difficulty in applying the mixing-length concept to heat- or mass-transfer is that the gradients of these entities do not always conform with the velocity-gradient used with known shear-stress to evaluate mixing-length. It is necessary, therefore, to amplify the expressions for mixing-length to carry across the mid-plane of zero shear-stress in a continuous manner.

The fundamental concept of mixing-length is the cross-stream distance in which the fluid properties at one plane are lost in another. This distance, ℓ, is of considerable magnitude, not an infinitesimal, and oscillations from a plane near that of maximum velocity will extend into regions of opposite shearing (see Fig. 2). This is contrary to the usual assumption of linear velocity-profile over a distance 2ℓ. Hence it is necessary to consider the combined effect of transporting separate instantaneous velocities at $(z + \ell)$ and $(z - \ell)$, respectively, to the shear-plane at z.

Expanding the concise explanation of shear-stress and turbulence-velocities given by O'Brien and Hickox [16, pp. 116-117] for two-dimensional flow, the instantaneous velocity-components are $u_{z+\ell} = U_{z+\ell} + u'_{z+\ell}$, $u_{z-\ell} = U_{z-\ell} + u'_{z-\ell}$, w = w', where U is the mean velocity. The time-averages of u' and w' are zero. The instantaneous rate of transfer of the X-component of momentum per unit-area at any point in the Z-direction is

$$-(\rho/2)\,[w'_{z+\ell}\,(U_{z+\ell} + u'_{z+\ell}) + w'_{z-\ell}\,(U_{z-\ell} + u'_{z-\ell})] \qquad (4a)$$

where ρ is the mass-density. The time-average of this momentum-transfer must correspond to a tractive force (shearing-force per unit-area, namely, shear-stress)

$$\tau = (1/t)\int_0^t \rho\left\{[(w'U)_{z+\ell} + (w'U)_{z-\ell}]/2 + [(w'u')_{z+\ell} + (w'u')_{z-\ell}]/2\right\}dt$$

where the time-interval, t, includes many fluctuations. Breaking this integral into two parts, the time-average of the first term is zero because U is constant and the time-average of w' is zero. Integrating the second term, assuming that ρ is constant:

$$\tau = -(\rho/2t)\int_0^t [(w'u')_{z+\ell} + (w'u')_{z-\ell}]dt = -(\rho/2)\,[\overline{(w'u')}_{z+\ell} + \overline{(w'u')}_{z-\ell})] \qquad (4b)$$

This reduces to the classical Reynolds expression [22, p. 554] for shear-stress in two-dimensional turbulent flow if $w'u'_{z+\ell} = w'u'_{z-\ell}$ as usually assumed.

O'Brien and Hickox show how the product (u'w') is always negative [when below the plane of $(dU/dz) = 0$] and hence the shear-stress in equation (4b) is positive unless $\overline{(w'u'_{z+\ell})}$ is from the opposite side of the midplane and overpowers $\overline{(w'u'_{z-\ell})}$. Thus for symmetrical flow between parallel plates the shear-stress goes to zero at the midplane not because $\overline{(u'w')}$ here is zero, but because the momentum-contributions represented by that product from two opposite sides are equal and balanced. This concept of net momentum-transfer in the region of maximum velocity might be compared with the common interpretation of evaporation as the net difference between co-existent rates of vaporization and of condensation.

The replacement of the average product $\overline{(u'w')}$ by a product of average magnitudes $\overline{|u'|}$ and $\overline{|w'|}$ with a correlation-factor, K, that is, $\overline{u'w'} = K\,\overline{|u'|} \times \overline{|w'|}$, involves a sign which must change in crossing z_m. Prandtl [19, 17 (pp. 137-138), 18] accommodates the change of sign in his basic equation by employing the magnitude symbol to keep the sign of shear-stress and velocity-gradient in agreement as in (4c).

$$\tau = \rho\,\ell^2\,(dU/dz)\,|dU/dz| \qquad (4c)$$

Prandtl obtained this equation assuming in effect that $\overline{|u'|} = \ell_u\,|dU/dz|$ and $\overline{|w'|} = \ell_w\,|dU/dz|$, and that $\overline{|w'|}$ was proportional to $\overline{|u'|}$, that is, $\ell_w = C\,\ell_u$. Then, retaining proper signs, $-\overline{|u'w'|} = K\,\ell_u\,(dU/dz)\,C\,\ell_u\,|dU/dz|$, in which $K\,C\,\ell_u^2$ is the ℓ^2 of equation (4c) and the correlation-factor K is considered always positive. It may be observed that the rate of momentum-transfer between two given strata is independent of the sign of w', because transfer in either direction tends to reduce whatever velocity-gradient exists across the path of w'.

In order to use the concept of unequal double contributions to shear-stress, the average

products $\overline{w'u'}_{z+\ell}$ and $\overline{w'u'}_{z-\ell}$ of equation (4b) must be separately determined. Expressing these in modified Prandtl form we have (see Fig. 2)

$$-\overline{w'u'}_{z+\ell} = \ell_z^2 \left[\left(\frac{dU}{dz}\right)\left|\frac{dU}{dz}\right|\right]_{z+(\ell/2)}$$

$$-\overline{w'u'}_{z-\ell} = \ell_z^2 \left[\left(\frac{dU}{dz}\right)\left|\frac{dU}{dz}\right|\right]_{z-(\ell/2)}$$

$$\tau = +(\rho/2)\,\ell_z^2\left\{\left(\frac{dU}{dz}\right)_{z+(\ell/2)}\left|\frac{dU}{dz}\right|_{z+(\ell/2)} + \left(\frac{dU}{dz}\right)_{z-(\ell/2)}\left|\frac{dU}{dz}\right|_{z-(\ell/2)}\right\}$$

Simplifying this by assuming an average value for $\left|\frac{dU}{dz}\right|_{z\pm(\ell/2)}$ which represents an average cross-velocity w', one obtains an expression utilizing the Prandtl mixing-length, which nevertheless permits transfer of heat or moisture across the zero momentum-plane as in (4d).

$$\tau \sim (\rho/2)^2 \left|\frac{dU}{dz}\right|_{z\pm(\ell/2)}\left\{\left(\frac{dU}{dz}\right)_{z+(\ell/2)} + \left(\frac{dU}{dz}\right)_{z-(\ell/2)}\right\} \qquad (4d)$$

If the velocity-profile near its maximum [for $(z-\ell) < z < (z+\ell)$] is parabolic, then $[(dU/dz)_{z+(\ell/2)} + (dU/dz)_{z-(\ell/2)}]/2 = (dU/dz)_z$ since (dU/dz is proportional to $(z_m - z)$. Thus

$$\tau \sim \rho\,\ell^2 \left|\frac{dU}{dz}\right|_{z\pm(\ell/2)} \left(\frac{dU}{dz}\right) \qquad (4e)$$

for the central zone of width 2ℓ.

It is to be noted that with such a parabolic profile, $\left|\frac{dU}{dz}\right|_{z\pm(\ell/2)}$ (and hence the eddy-diffusivity, ordinarily defined as $\epsilon = \ell^2\left|\frac{dU}{dz}\right|$), would be constant across the central zone of width ℓ (half as wide as the zone for which the profile was considered parabolic). This indicates that for ℓ constant in this region, shear-stress would be directly proportional to velocity-gradient, rather than to the square (as in the original Prandtl equation).

Evaluation of mixing-length--Nikuradse [14] used the Prandtl equation for evaluating mixing-length from observations of velocity-profiles of water flowing in pipe, under known pressure-gradients. He found that mixing-length is primarily a function of the fractional distance from the surface to the zero-shear line (center of pipe). Nikuradse shows that ℓ is not dependent on the magnitudes of velocity-gradient and shear-stress, except for a slight change with Reynolds' number. He finds that near the wall $(\ell/r_o) = (0.36 \text{ to } 0.38)\, y/r_o$, and near the center of pipe (ℓ/r_o) approaches a constant value, 0.14 to 0.15, for given magnitudes of the Reynolds' modulus. Nikuradse's expression for the curve at Reynolds' number 3×10^6 is

$$(\ell/r_o) = 0.14 - 0.08\,(1 - z/r_o)^2 - 0.06\,(1 - z/r_o)^4 \qquad (5a)$$

An alternate expression is the hyperbolic tangent $(\ell/z_m) = 0.14 \tanh (2.6\, z/z_m)$ and the reciprocal is well represented by (5b).

$$(z_m/\ell) = 2.5\,[(z/z_m) + (z_m/z)] + 2.0 \qquad \text{for } z \leq z_m \qquad (5b)$$

Although Nikuradse [using the original Prandtl equation (4c)] found that the value of mixing-length does not change appreciably within the central zone, this result is dependent upon a rate of change of velocity-gradient more rapid near $z = z_m$ than farther from the center. In view of the difficulty of empirical determination of velocity-gradients, a slightly different interpretation of velocity-data might be made with equal validity, finding constant mixing-length in the central zone consistent with the modified shear-stress equation (4e).

There may be some question regarding the extrapolation of Nikuradse's findings in relatively small pipes to outdoor density-currents where z_m is of the order of 30 feet, but this should be possible with due attention to Reynolds' number. The velocity at a height of 20 feet can be taken as the mean for a channel-width of, say, 60 feet. This velocity is roughly three feet per second and the kinematic viscosity of air at 32°F is 1.423×10^{-4} ft^2/sec. Hence the channel Re is of the order of 1260×10^3. This is within the range of Nikuradse's experiments, which extended, in

terms of pipe Reynolds' numbers, from 9×10^3 to 3070×10^3. For large-scale two-dimensional flow such as winds well above the ground-surface, there should be some asymptotic limit to mixing-length. Brunt [2, p. 216] suggests a linear dimension of disturbance based on fluid characteristics and intensity of turbulence.

The von Kármán derivation of mixing-length [11, pp. 7-8] assumes similar flow-patterns, in which case the ratio of successive derivatives of the velocity-profile gives a significant length. His expression is

$$\ell = \kappa \left| \frac{(dU/dz)}{(d^2U/dz^2)} \right| \qquad (5c)$$

where κ is the Kármán constant, found equal to 0.4 for fluids flowing under pressure stream-line gradient uniformly distributed across the flow-section. Von Kármán states that: "The assumption of similar flow-patterns is identical with the assumption of constant correlation between the components of the velocity-fluctuations (u', w')", and he shows by data from Wattendorf (California Institute of Technology) and from Reichardt (Göttingen) that this is constant only from 0.1 to 0.6 of the distance from channel-wall to midstream. This severe limitation by correlation is restricted further in density-currents because of non-uniform distribution of pressure stream-line gradient. Hence von Kármán's expression for mixing-length appears useful only as an approximate indicator. This may be valuable, however, in locating approximately the equivalent smooth plane for the rough surface of tops of trees.

Prandtl's concept of eddy-dynamics relates mixing-length and velocity-gradient to shear-stress without any qualifying restriction in the equivalent Reynolds' expression for the rate of change of shear-stress with height. Hence this equation should be applicable to density-currents (with their non-uniform vertical distribution of pressure stream-line gradient), except in the region of maximum velocity. It may be necessary, however, to alter the evaluation of mixing-length, which heretofore has been based on experiments in fluid flow in pipes for which the distribution of pressure stream-line gradient (dP/dx) was uniform across the section of flow.

In the absence of buoyancy-stratification, one can see from Prandtl's equation that for the same density and same magnitude of shear-stress at a given distance from a smooth surface one must find the same value for the product of mixing-length times velocity-gradient whether the flow is due to a uniform distribution of pressure stream-line gradient (as in flow in pipes), or to non-uniform distribution of density stream-line gradient (as along a vertical hot plate). The importance of this dual applicability is that velocity-gradients are readily observable. Hence the various characteristics of the flow can be determined if either the mixing-length or shear-stress is known. Thus Prandtl's mixing-length is an overall concept of whatever factors need to be used with any observed velocity-gradient to yield the concurrent "push-friction" velocity.

Velocity-equation for fluid flow above a surface; non-linear shear-stress distribution--In the shear-stress equation (4e) the magnitude-average velocity-gradient $\left|\frac{dU}{dz}\right|_{z \pm (\ell/2)}$ would be invariant over the range $(z_m \pm \ell/2)$ if the velocity-profile across the plane of maximum velocity can be properly represented by a parabola. This is a reasonable assumption because Nikuradse's data can be fitted from z_m to $(z/z_m) = 0.6$ by a parabola of degree 1.7. [Nikuradse, in Forschungsheft 361, used a similar method (Fig. 17) for fitting the velocity-profile from (z/z_m) of 0.5 to 1.0 by a parabola of degree 1.5.] Thus the exponent of velocity-gradient in the shear-stress equation should change from 2 to unity as the plane of maximum velocity is approached. The transition from equation (4c) to (4e) might be expressed as

$$\tau = \rho \ell^2 \left\{ f(z) \left(\frac{dU}{dz}\right) \left|\frac{dU}{dz}\right| + [(1 - f(z)] \left(\frac{dU}{dz}\right) \left|\frac{dU}{dz}\right|_{z \pm (\ell/2)} \right\} \qquad (4f)$$

where $f(z) = 1$ for $0 < (z/z_m) < 0.6$, and $f(z) = 0$ at $(z/z_m) = 1.0$. The nature of $f(z)$ for $0.6 < (z/z_m) < 1.0$ should be consistent with a regular variation of mixing-length ℓ approaching a maximum as found by Nikuradse. The value of $0.6\ (z/z_m)$ is selected arbitrarily to coincide with the breakdown of constant correlation cited by von Kármán.

A table of values for (dU/dz) from the buffer layer at the wall to $(z/z_m) = 0.6$ can be constructed, using the Prandtl expression (4c) relating shear-stress, mixing-length, and velocity-gradient as in (6).

$$(dU/dz) = + (1/\ell) \sqrt{\tau/\rho} \quad \text{for } \tau > 0 \quad \text{and} \quad (dU/dz) = - (1/\ell) \sqrt{-\tau/\rho} \quad \text{for } \tau < 0 \qquad (6)$$

taking the mixing-length and shear-stress as functions of height, z.

An attempt to carry the calculation by the original Prandtl equation much beyond $(z/z_m) = 0.6$ with the Nikuradse mixing-length function will introduce a reversal of curvature in (dU/dz).

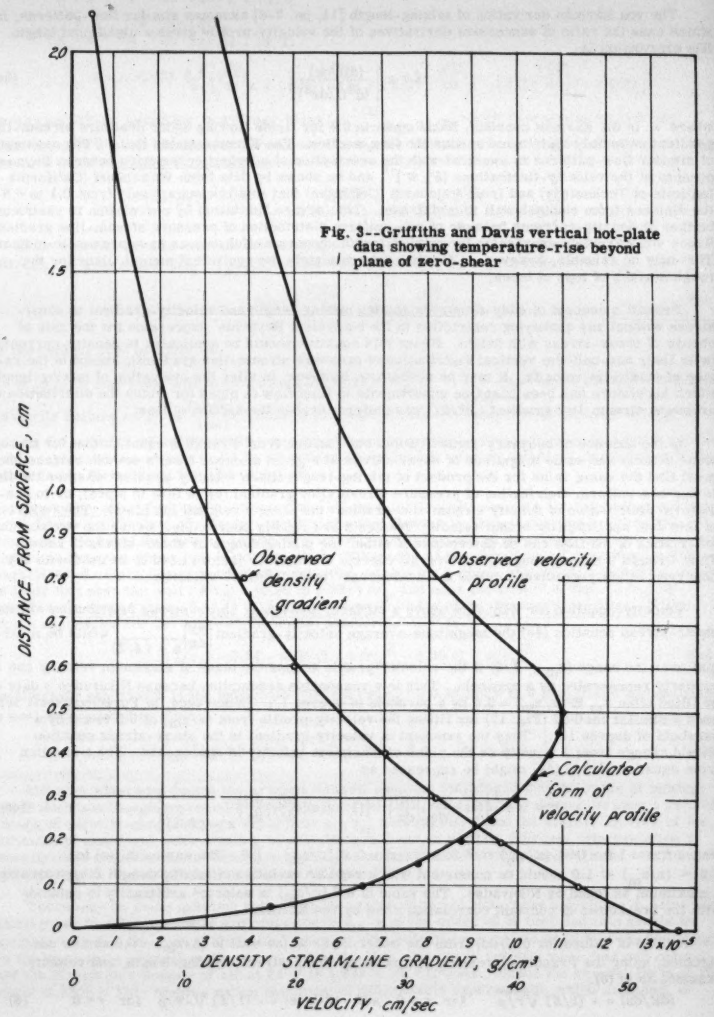

Fig. 3--Griffiths and Davis vertical hot-plate data showing temperature-rise beyond plane of zero-shear

The transition indicated in equation (4f) can be accomplished graphically by plotting (dU/dz) up to $(z/z_m) = 0.6$ or 0.7, then drawing a tangent which passes through $(dU/dz) = 0$ at $z = z_m$. Then a new function can be fitted over the entire range of (dU/dz), which can be integrated analytically to obtain an equation for velocity-distribution.

The data of Griffiths and Davis [6, Fig. 6] show velocity- and temperature-profiles for thermal convection along a vertical hot plate (see Fig. 3). Griffiths and Davis state that the flow must be turbulent (although at low Reynolds' number). For this example, one finds that the density stream-line gradients for the 72.0-cm station can be expressed as $p_{x\theta} = 0.000133\ e^{-1.585z}$, where $p_{x\theta}$ is in (gm/cm^2) per cm and z is in cm. In this case of vertical transport the barometric term (p_{xb}) is zero; hence the expression for shear-stress is

$$\tau = \int_z^{z_m} p_{x\theta}\, dz = + (0.000133/1.585)\,(e^{-1.585\,z} - e^{-1.585\,z_m})$$

The maximum velocity occurs at $z_m = 0.5$ cm; thus the shear-stress is evaluated from $\tau = 0.000084\,(e^{-1.585\,z} - e^{-0.7925})$.

Taking square roots of these values and multiplying by $1/(\ell/\rho)$, one obtains an empirical curve for (dU/dz) from the surface to $(z/z_m) = 0.6$ which is well fitted by the function

$$(dU/dz) = Az^{-1} + B + Dz \tag{7}$$

Upon integration this leads to a velocity-expression for the range $0 < (z/z_m) < 0.6$ of the familiar logarithmic type as in (8a).

$$(U_{max} - U) = 2.3A \log_{10} z + Bz + (D/2)\, z^2 + C \tag{8a}$$

If the velocity-gradient from $(z/z_m) = 0.6$ to 1.0 is assumed linear, the velocity-equation for this portion of the profile will be a parabola as in (8b).

$$(U_{max} - U) = E(z_m - z)^2 \tag{8b}$$

This parabolic expression is applicable for a short distance past the plane of maximum velocity. Beyond this region, in this example, large fluid masses are being accelerated and physical conditions require an inflection point in the velocity-profile (which must approach zero at infinite distance from the plate).

Since equation (8a) is similar to the common expression for velocity in flow in pipe, it is evident that the shape of the velocity-profile is rather insensitive to the distribution of shear-stress. Hence one cannot tell by inspection of the velocity-distribution near the surface whether the current is due to uniformly or non-uniformly distributed pressure stream-line gradient.

Heat-transfer by eddy-diffusion--The quantity of heat transferred by a volume V of fluid moving through a cross-stream distance ℓ (in conformity with the mixing-length concept) will be $Q = -\rho g V c_p \ell (d\theta/dz)$, where g is the acceleration of gravity, c_p is specific heat at constant pressure, and θ is the potential temperature. The derivation of an equivalent expression is given by Goldstein [5 (v. 2, p. 648), 25 (pp. 2-11)].

The corresponding heat-transfer rate per unit-area in the shear-plane, is

$$(q/A) = -\rho g c_p \overline{|w'|}\, \ell (d\theta/dz) \tag{9a}$$

where $\overline{|w'|}$ is the average magnitude of vertical oscillations. As in the shear-stress (momentum-transfer) equation, the direction of the vertical motion is not involved. Local motion either upward or downward in the presence of temperature-stratification has the effect of transferring heat in the direction of descending temperature. Employing the double-contribution principle previously introduced in connection with momentum-transfer, the mean vertical velocity will have the form

$$\overline{|w'|} \sim (\ell/2)\left[\left|\frac{dU}{dz}\right|_{z\,-\,(\ell/2)} + \left|\frac{dU}{dz}\right|_{z\,+\,(\ell/2)}\right]$$

The corresponding form of heat-transfer expression is

$$\left.\begin{aligned} (q/A) &\sim -\left[(\rho\, g\, c_p\, \ell^2)/2\right]\left[\left|\frac{dU}{dz}\right|_{z-(\ell/2)} + \left|\frac{dU}{dz}\right|_{z+(\ell/2)}\right]\frac{d\theta}{dz} \\ \text{or} \quad (q/A) &\sim -\rho\, g\, c_p\, \ell^2 \left|\frac{dU}{dz}\right|_{z\pm(\ell/2)} (d\,\theta/dz) \end{aligned}\right\} \qquad (9b)$$

which permits transfer across the plane of zero velocity-gradient. In brief, with a corrected definition of eddy-diffusivity, one may retain the usual form

$$(q/A) \sim -g\, c_p\, \rho\, \epsilon\, (d\,\theta/dz) \qquad (9c)$$

where the eddy-diffusivity

$$\epsilon \sim \ell^2 \left|\frac{dU}{dz}\right|_{z\pm(\ell/2)}$$

and $\rho\epsilon$ is the "austauch" coefficient. It is observed that this definition avoids the zero-value for ϵ at $(z/z_m) = 1.0$ which would result from Prandtl's original equation. Nikuradse acknowledges the need for such a correction in his discussion of Figure 27 in Forschungsheft 356, indicating an arbitrary minimum value of ϵ at the stream center. As remarked previously [after equation (4e)]; a parabolic profile near the maximum velocity-plane would correspond to a constant ϵ in that region. Goldstein [5, p. 587] discusses this problem briefly.

Effect of buoyancy-stratification--The well-known stability discussion of Rossby and Montgomery [24, pp. 47-48] has been subject to criticism. Brunt [2, pp.249-251] gives an account of this derivation, expressing dissatisfaction with the assumption that the Prandtl shear-stress equation remains applicable to stable atmospheres on insertion of a corrected expression for the mixing-length. Rossby and Montgomery reach the conclusion that the vertical gradient of wind-velocity increases with degree of inversion, for a given shear-stress. This is contrary to Flower's [4, p. 68] finding that "The development of a very large inversion is not therefore associated with a corresponding increase in velocity-gradient, but instead appears to be accompanied by a slight decrease."

The authors believe that, since for a given shear-stress the buoyancy-stratification affords an additional means of dissipation of energy (conversion into unavailable form), the velocity-gradient should be reduced under stable conditions. In the presence of stability $[(d\,\theta/dz) > 0]$ the observed gradient $(dU/dz)_s$ involves a greater dissipation of energy (hence greater supply) than an observed gradient $(dU/dz)_n$ of equal magnitude for the neutral atmospheric dondition, $(d\,\theta/dz) = 0$ (where no buoyant forces exist).

The first Rossby-Montgomery equation (93) [or Brunt (75)] states equivalence of total dissipation of energy for stable and for neutral atmospheres in which the same rate of shear (velocity-gradient) is maintained. There is no apparent justification for such a relationship, since (with equal rates of shear) the shear-stresses are thereby implicitly regarded as the same under the two conditions. The resulting expression (94) [or Brunt (77)] gives the necessary value of mixing-length under stable conditions to fit the (seemingly impossible) situation described by the original equation (93).

The confusion arising from the Rossby-Montgomery equation may be avoided by treating the conditions of equal shear-stress and equal velocity-gradient in two separate lines of argument. First, equal shear-stresses may be applied to neutral and stable atmospheres, and a relation between the resulting velocity-gradients may be determined. Second, equal velocity-gradients may be postulated, and the shear-stresses required to maintain them may be compared for the two atmospheric conditions. For simplicity, both arguments are based on comparison of rates of momentum-transfer and velocity-gradients for a fixed geometrical definition of the mixing-length. That is, the dissipation of energy is compared for moving unit-masses of fluid through equal cross-stream distances.

(A) Equal shear-stresses applied to neutral and stable atmospheres--For the neutral case the shear-stress will be represented by the Prandtl expression

$$\left|\tau_n\right| = \rho\, \ell^2\, (dU/dz)_n \qquad (10a)$$

and for the stable atmosphere, the shear-stress (equal to work per unit-volume in relative motion) is consumed, or opposed, by a thermal-dissipation term as well as by the turbulent momentum-transfer

$$|\tau_s| = \rho \ell^2 [(dU/dz)_s^2 + (g/\Theta)(d\Theta/dz)] \tag{10b}$$

Equating equations (10a) and (10b), and solving for the rate of shear (velocity-gradient) in the stable atmosphere, we have (11).

$$(dU/dz)_s = [(dU/dz)_n^2 - (g/\Theta)(d\Theta/dz)]^{1/2} \tag{11}$$

The rate of energy-dissipation per unit-region (stationary volume) is given by the product $\tau\,(dU/dz)$. Hence for Rossby and Montgomery to assume [in their equation (93)] equal energy-dissipation and equal velocity-gradient must indicate also equal shear-stress, which seems incompatible with an additional mode of energy-dissipation under stable stratification. Energy-rates should be compared only for the same stationary unit-volumes; hence it appears improper to consider different mixing-lengths for neutral and for stable cases.

The energy-dissipation rates for a given region under neutral and under stable conditions for equal applied shear-stresses are therefore unequal and are given by (12a) and (12b).

$$E_n = \rho \ell^2 (dU/dz)_n^3 \tag{12a}$$

$$\begin{aligned} E_s &= \rho \ell^2 (dU/dz)_s [(dU/dz)_s^2 + (g/\Theta)(d\Theta/dz)] \\ &= \rho \ell^2 (dU/dz)_s (dU/dz)_n^2 \end{aligned} \tag{12b}$$

Since for equal shear-stress $(dU/dz)_s < (dU/dz)_n$ by equation (11), the condition of stability reduces the total energy-dissipation in the fluid, provided the pressure stream-line gradient distribution (hence the shear-stress) is the same.

The relations between velocity-gradients and total energy-dissipations given by equations (11) and (12) may be expressed conveniently in terms of an alternate form of the Richardson criterion of stability [23; 13 (pp. 248-249)]. According to Richardson's discussion, the critical condition for the dying away of turbulence occurs when the thermal-dissipation term (work done against buoyant forces) just equals the "energy-supply from eddies." He states that the latter quantity is measured by the square of velocity-gradient which, by the unaltered Prandtl equation, is proportional to shear-stress. The ratio of the thermal-dissipation term to the "energy-supply from eddies" (elsewhere defined as "work of eddy-stresses") has been denoted by

$$Ri = (g/\Theta)(d\Theta/dz)/(dU/dz)_s^2 \tag{13a}$$

where $(d\Theta/dz)$ and (dU/dz) are, presumably, simultaneously observed (hence the subscript s). This is the criterion whose value of unity was observed by Flower [4] to coincide with the disappearance of atmospheric turbulence. Other writers [7 (p. 200); 2 (pp. 242, 249-250)] have indicated various numerical factors attached to the numerator (thermal term) which, in effect, alter the magnitude of the Richardson criterion observed or predicted as "critical" for eddy-decay.

If it is true that buoyancy-stratification affords an additional means of energy-dissipation, it follows that an observed velocity-gradient does not uniquely determine the incident shear-stress, or vice versa [see equations (10)]. Richardson's concept of "energy-supply from eddies" which forms the denominator of the criterion (13a), should therefore be replaced by "supply of kinetic energy to eddies," measured by the incident shear-stress (integrated pressure stream-line gradient) and hence by $[(dU/dz)_s^2 + (g/\Theta)(d\Theta/dz)]$ instead of $(dU/dz)_s^2$. The authors believe that Richardson, in effect, has set up a comparison of the thermally-dissipated portion of shear-energy to the remaining portion (evaluated by observing the velocity-gradient), and that a less ambiguous criterion would be given by the ratio of the former (thermal term) to the total shear-energy, as in (13b).

$$Ri' = (g/\Theta)(d\Theta/dz)/[(dU/dz)_s^2 + (g/\Theta)(d\Theta/dz)] \tag{13b}$$

A comparison of equations (13a) and (13b) reveals the simple relation

$$Ri' = Ri/(Ri + 1) \tag{13c}$$

Both forms of the criterion take the value zero for neutral atmospheres (zero-gradient of potential temperature). The condition of ultimate stability, corresponding to a complete dying away of turbulence, is denoted by Ri = ∞ and Ri′ = 1. These limiting magnitudes require a velocity-gradient of zero in equations (13a) and (13b), respectively, although a residual laminar flow may exist.

Returning to the comparison of velocity-gradients and total energy-dissipations for equal applied shear-stress in neutral and stable atmospheres, the alternate criterion Ri′ will be utilized to simplify the relations. Substitution of the expression (13b) into equations (11) and (12) yields

$$(dU/dz)_s = (dU/dz)_n (1 - Ri')^{1/2} \tag{14}$$

and

$$E_s = E_n (1 - Ri')^{1/2} \tag{15}$$

The significance of the zero- and unity-values of the alternate Richardson criterion Ri′ is shown clearly in equations (14) and (15). For the zero-value, the neutral-atmosphere conditions hold; for the maximum possible value (Ri′ = 1), the energy available to maintain turbulence is entirely consumed in work against thermal stratification. Anemometer traces given by Flower [4, pp. 72-76] show that a unity value of the original Richardson criterion Ri coincides with the extinction of wind-eddies. This corresponds to a magnitude Ri′ = 1/2 for the alternate criterion. In view of the ambiguity in Richardson's derivation, this result may explain the discrepancy between critical values of the criterion cited by Brunt and Haurwitz [2,7] in discussing the contributions of Prandtl and Taylor to the stability-problem.

(B) Same velocity-gradient to be maintained in neutral and stable atmospheres--Combining equations (10a) and (10b) for the condition $(dU/dz)_n = (dU/dz)_s = (dU/dz)$, the shear-stresses required for neutral and stable atmospheres are as in (16a) and (16b).

$$|\tau_n| = \rho \ell^2 (dU/dz)^2 \tag{16a}$$

$$|\tau_s| = \rho \ell^2 [(dU/dz)^2 + (g/\Theta)(d\Theta/dz)] \tag{16b}$$

Clearly, then, a greater applied pressure stream-line gradient is necessary to maintain a given flow-pattern when buoyancy-stratification is introduced. Again, the mixing-lengths must be alike for effective comparison of momentum-transfer rates. Since the velocity-gradients are equal, the total regional rates of energy-dissipation [$E = \tau (dU/dz)$] will be in proportion to the shear-stresses applied as in (17a) and (17b).

$$E_n = \rho \ell^2 (dU/dz)^3 \tag{17a}$$

$$E_s = \rho \ell^2 (dU/dz) [(dU/dz)^2 + (g/\Theta)(d\Theta/dz)] \tag{17b}$$

The energy-dissipation rate in the presence of atmospheric stability is necessarily greater, because in this discussion equal velocity-gradients are being maintained with and without stability.

Certain recorded observations of higher wind-velocity at night might be considered contradictory to the above conclusion, excepting that:

(1) Density-currents often in themselves have pressure-gradients a hundred times stronger than the barometric gradient-component.
(2) Above the inversions the topographic roughness is somewhat lessened because pools of cold air partially fill valley-bottoms.
(3) There is an absence of large-scale thermal convection, which in the daytime promotes momentum-transfer.

As in the previous argument, the relations may be stated conveniently in terms of the alternate Richardson criterion Ri′. For equal velocity-gradients

$$\tau_s = \tau_n (1 + Ri') \tag{18}$$

$$E_s = E_n (1 + Ri') \tag{19}$$

The relations for shear-stress and energy are in the same proportion for equal rates of shear (velocity-gradients), and the ratio becomes unity for a zero of the criterion. It is interesting to note that as Ri′ → 1.0 (Ri → ∞) (condition of ultimate stability) the required shear-stress and

energy-supply to maintain a given flow-pattern become twice the corresponding magnitudes for zero-stability. This result may be of independent significance in connection with the discussion [2,7] of the correct critical value of the criterion of stability.

In the 25th Wilbur Wright Memorial Lecture, von Kármán [12, Fig. 21] cites measurements of time-correlation of velocity-fluctuations by Kuethe, which show an apparent turbulent kinetic energy-ratio between stable and unstable atmospheres of approximately 1/3. This condition, assuming the same incident shear-stress pattern, corresponds [according to equation (15)] to stability criteria $Ri' = 8/9$ and $Ri = 8$; indicating turbulent flow beyond the critical stability-condition observed by Flower.

Velocity-equation for density-currents--The Prandtl equation connects velocity-gradient, shear-stress, and mixing-length, but this shear-stress is strictly that available for maintaining kinetic turbulence. Equation (10b) shows that the whole shear-stress, τ_s, as determined by integrating the pressure-gradient, equation (3b), is apportioned to kinetic turbulence and thermal-energy dissipation. Hence the velocity-equation (except in the central zone previously discussed) is the integral of

$$(dU/dz)_s = [\tau_s/\rho \ell^2 - (g/\Theta)(d\Theta/dz)]^{1/2} \qquad (20)$$

The use of this equation requires the expression of temperature-gradient as a function of height, z. Inasmuch as the thermal term is under the radical, it seems best to calculate (dU/dz) point by point and then fit an expression similar to equation (7). Again, this will yield a velocity-expression (applying from the buffer layer up to the neighborhood of the maximum-velocity plane) not unlike the common equation for fluid flow in channels. To carry the analysis across the central zone, a transition equivalent to that represented by equation (4f) is needed to introduce the direct proportionality between velocity-gradient and reduced (by the thermal term) shear-stress [equation (20) with the radical removed] which is applicable at the plane of maximum velocity.

Conclusion--In brief, modifications have been shown necessary in the Prandtl equation relating shear-stress, velocity-gradient, and mixing-length, to make it applicable to density-currents in which the distribution of pressure stream-line gradient is not uniform. The geometric concept of mixing-length yields consistent results and can be used in an expanded manner to permit the transfer of heat and moisture across the plane of zero momentum-transfer. The mixing-length need not be considered to vary with stability, and should be considered unaltered in comparing shear-stresses and energy-dissipation rates for systems in which only the degree of density-stratification is different.

It is noted that von Kármán identifies his assumption of similar flow-patterns with the region of constant correlation of the turbulent velocity-components, which, according to data cited by him, extends only from 0.1 to 0.6 of the distance from wall to midstream. This restricts the utility of the von Kármán definition of mixing-length in terms of ratio of successive velocity-derivatives.

It is shown that buoyancy-stability decreases the shear-energy available for maintenance of kinetic turbulence. Therefore, the velocity-equation for density-currents is based on the integrated pressure stream-line gradient reduced by the thermal-stability term. For the same reason, a given observed velocity-gradient will not uniquely determine the shear-stress pattern, although it will determine the eddy-diffusivity applicable to transfer of heat and mass. The shape of the velocity-profile seems unexpectedly insensitive to the imposed conditions. Hence one cannot by inspection of the form of the velocity-profile near the surface draw reliable conclusions as to the incident shear-stresses.

In considering flow-patterns under neutral and under stable conditions, it is necessary to distinguish between rates of energy-dissipation and rates of shear-stress (momentum-transfer). A shear-stress represents work done per unit-volume of cross-stream transfer, while energy-dissipation is work done per unit-time in maintaining turbulent motion in a fixed unit-volume. To consider the two concepts synonymous is incorrect, because their dimensions differ by velocity-gradient [energy-dissipation rate in a fixed region $\sim \tau\,(dU/dz)$]. This, the authors believe, is the essential difficulty with the Rossby-Montgomery derivation which leads to the untenable conclusion that to add stability reduces fluid friction. A similar confusion may be responsible for the ambiguity in Richardson's development of the stability-criterion.

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A STABILITY-TERM IN THE WIND-GRADIENT EQUATION

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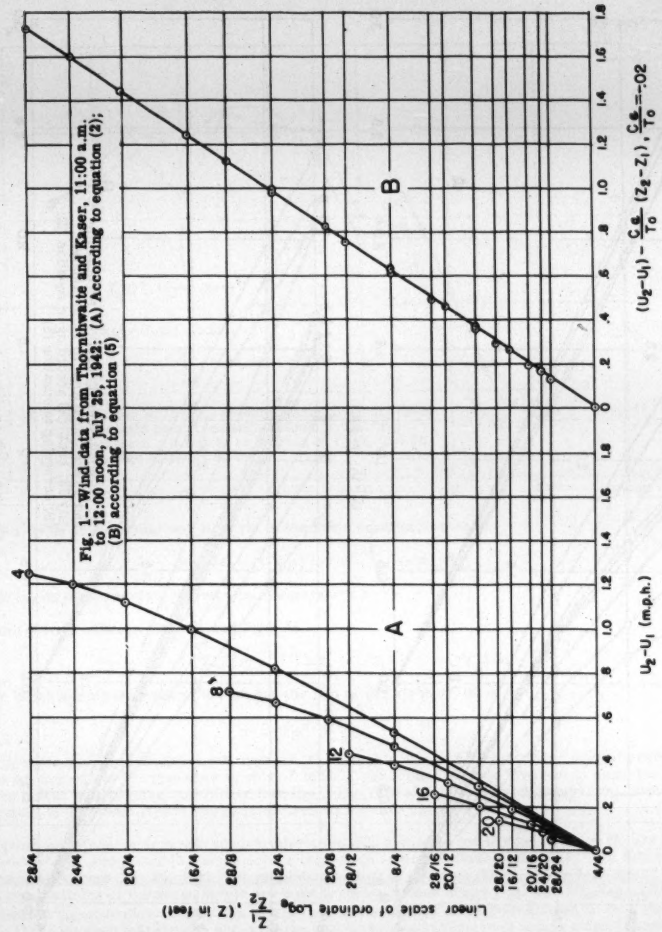
In considering the variation of wind-velocity with distance from a solid boundary, many workers have used a basic equation derived from Prandtl's work [see 1 of "References" at end of paper]. This equation is

$$(du/dz) = (1/k_0 z)\,(\tau/\rho)^{1/2} \qquad (1)$$

where u = mean wind-velocity, z = distance from surface, k_0 = turbulence constant of von Kármán, τ = shear-stress, ρ = density. When k_0, τ, and ρ are considered constant near the boundary-surface, equation (1) may be integrated between two levels [2] giving equation (2).

$$(u_2 - u_1) = (1/k_0)\,(\tau/\rho)^{1/2} \log_e (z_2/z_1) \qquad (2)$$

This equation is in good agreement with observations made under conditions of neutral equilibrium, but does not fit records covering periods of pronounced surface heating or cooling.



It might at first appear that this discrepancy results from the assumption of a constant density. However, if we allow a linear variation of temperature with height to govern variations in density in equation (1), integration leads to

$$(u_2 - u_1) = (1/k_o)\,(\tau/\rho_o)^{1/2}\,[(\alpha/T_o)\,(z_2 - z_1) + \log_e\,(z_2/z_1)] \qquad (3)$$

in which α is the lapse-rate and T_o is the surface-temperature. It can be seen that $(\alpha/T_o)\,(z_2 - z_1)$ will seldom give a correction of more than one or two per cent, since the numer-

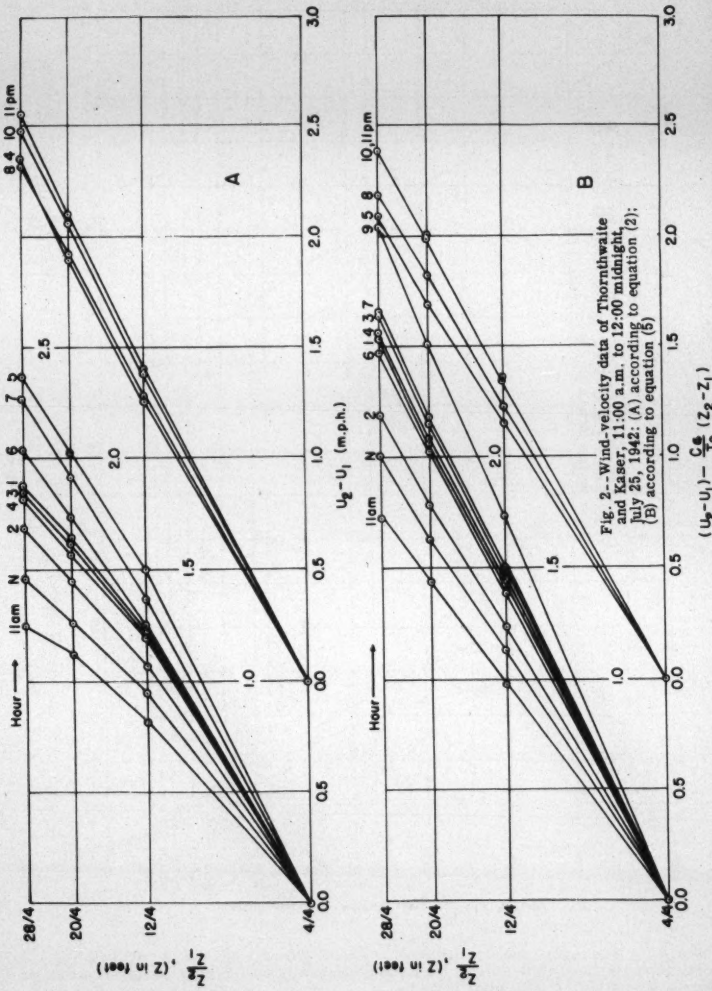


Fig. 2.--Wind-velocity data of Thornthwaite and Kaser, 11:00 a.m. to 12:00 midnight, July 25, 1942: (A) according to equation (2); (B) according to equation (5)

ator is the difference of temperature in degrees, while the denominator is the surface-temperature in degrees absolute. The assumption of a constant density is therefore justified.

It is obvious that the effect of stability is much more fundamental. If we assume that the

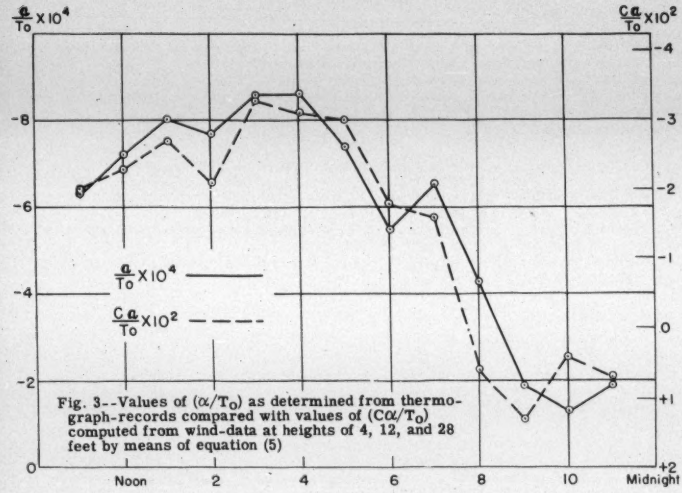


Fig. 3--Values of (α/T_o) as determined from thermograph-records compared with values of $(C\alpha/T_o)$ computed from wind-data at heights of 4, 12, and 28 feet by means of equation (5)

stability-term is superimposed linearly in the basic equation, we have

$$(du/dz) = (1/k_o z)(\tau/\rho)^{1/2} + (c\,\alpha_p/T_o) \qquad (4)$$

where α_p is the lapse-rate of potential temperature.

Integration between levels 1 and 2 yields

$$(u_2 - u_1) = (1/k_o)(\tau/\rho)^{1/2} \log_e (z_2/z_1) + (c\,\alpha_p/T_o)(z_2 - z_1) \qquad (5)$$

which is the same as equation (2) with the addition of the stability-term

$$(c\,\alpha_p/T_o)(z_2 - z_1) \qquad (6)$$

This term is positive for stable air, negative for unstable air, and drops out for neutral equilibrium. Since the dry adiabatic lapse-rate is only -0.0055° F per foot, the error involved in using the lapse-rate of actual temperature, α, rather than the lapse-rate of potential temperature, α_p, should be negligible in the lower layers where large lapse-rates are encountered.

Probably the most accurate wind-gradient records available for testing equation (5) are those of Thornthwaite and Kaser [3], taken over a level field at New Philadelphia, Ohio. The data for the hour ending at noon July 25, 1942, are plotted according to equation (2) in Figure 1-A, where various combinations of the seven levels are used to obtain values of $(u_2 - u_1)$ and $\log_e (z_2/z_1)$. If the unmodified logarithmic law, equation (2), is to be satisfied, all of the points must lie on a straight line. It can be seen that they do not, with the characteristic curvature of wind-profiles in unstable air appearing in the independent combinations.

Figure 1-B shows the same data plotted according to equation (5), and it can be seen that a value of -0.02 for $(c\,\alpha/T_o)$ brings all of the points to a straight line.

In the absence of detailed temperature-data, we may evaluate $(c\,\alpha/T_o)$ from the wind-records of three levels. This has been done in Figure 2-B, where hourly wind-profiles from 11 a.m. to midnight are shown, with the record of a fourth level serving as a check. The curvature which the same records exhibited when plotted according to the unmodified logarithmic law (Fig. 2-A) has

been completely eliminated.

In conjunction with the wind-data used in Figures 1 and 2, thermograph-records were taken at heights of two and eight feet, from which it was possible to evaluate (α/T_o). Since α will have its greatest variation near the ground, such a value must be taken as only an approximation to that prevailing between four and 28 feet, where the wind-records were obtained. Nevertheless, the correlation between the values of ($c\,\alpha/T_o$) computed from the wind-data and (α/T_o) as observed is high, as can be seen in Figure 3.

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EFFICIENT SAMPLING OF CLIMATIC AND RELATED ENVIRONMENTAL FACTORS

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Objectives in sampling

In the measurement of precipitation, interception, evaporation, and similar environmental factors it is frequently desired to obtain a reliable average figure for a land-area of substantial size, such as a cropped field, a forested plot, or a watershed. Often the observed factor is characterized by considerable variation; each day and location sampled provides a different value for the factor. Observations made under such conditions at a single location, even over a period of time, are not likely to give a good average figure for the entire area; they supply information only on the immediate vicinity of the sampling point. The soundest procedure is to take a number of observations by some scheme of randomization. By this process unbiased estimates can be obtained of the true mean value for the factor on the whole area, and of the error of the sample mean in approximating the true value.

Intensive sampling is often considered impractical, as few research organizations have the funds and personnel to purchase, and especially to operate and analyze the records from a large number of rain-gages, hygrographs, or other recording instruments. Actually, however, the requirements of adequate random sampling may frequently be satisfied without the need for heavy investments in equipment and time. The proposed method employs only a few instruments which are moved at frequent intervals from place to place in the area under observation. With this technique total or average values for any area can be obtained with a minimum of work and with little loss in precision as compared to the use of a relatively large number of instruments at fixed locations. The main requirements are that the necessary equipment be reasonably portable and that reliable average figures for a season or other period of time be more important than comparisons between individual days; although even daily comparisons may be obtained with fair precision.

On the following pages are discussed briefly the characteristics of variation, and examples are given of sampling by the suggested method without going into the details of statistical analysis, which are discussed in several excellent publications [see 2, 3, and 6 in "References" at end of paper].

Characteristics of variation

Any factor to be sampled may be thought of as characterized by a true mean value μ for a given season or other time-period, and by variation within the area to be studied due to two general sources: A component ϵ associated with the position of any single sample in the area, and a second component η due to time in the season. Then the magnitude of a single observation x, taken at the j^{th} position in the area on the i^{th} day of the season, may be expressed as $x_{ij} = \mu + \eta_i + \epsilon_{ij}$, in which η_i is the deviation (either positive or negative) of the observation from μ due to the particular day on which it was taken, and ϵ_{ij} is the corresponding deviation due to position. The magnitude of

the time-component is common to all observations taken on that day, while the place-component is peculiar to each sample taken on the day in question. If both are random and independent in the probability sense, the mean value of each or their joint value will become smaller with increasing numbers of observations, reaching zero when the whole area and season have been covered.

Let it be assumed that a complete enumeration is impractical, and that instead a random sample must be taken of the whole population of places and days represented by the area and season. Now the true value μ and the true variance σ^2 (squared standard deviation) of the population can not be known exactly; it is possible, however, to obtain a sample average and an estimate of the error of this average in approximating If $x_1, x_2, \ldots x_n$ are n values of a random variable whose true mean and variance are μ and σ^2, then ($\bar{x}$ being the mean of the observed sample values and s^2 their variance), $S(x - \bar{x})^2/(n - 1) = s^2$, which provides an estimate of σ^2. If the whole sample is made up of n observations, the variance of their mean is equal to (s^2/n); the variance of their sum is ns^2; and the square root of either value (standard error of the sample mean or sum) provides an estimate of the failure of the sample mean or sum to equal the population value μ [2, 3, 6].

In the sampling problem under discussion there are two categories of variation (time and space), each of which may be described by a variance, so that the variance of a single observation x may be expressed as $s^2_x = (s^2_\eta + s^2_\epsilon)$ and the variance of the mean of samples taken at n new places on each of k days, neglecting the correction for a finite population, which adjusts the error variance of means to zero as n becomes equal to the total population, is $s^2_{\bar{x}} = s^2_\eta/k + s^2_\epsilon/kn$; that is, the variance of the mean is reduced in proportion to the number of samples taken in each category of variation. If the daily sampling-observations are taken repeatedly at the same places, then $s^2_{\bar{x}} = s^2_\eta/k + s^2_\epsilon/n$. And if a single instrument is left continuously at the same place, the variance ϵ associated with position is not reduced. If the position variance is large, this procedure may involve a serious error in estimating the population-value, simply because the available data describe only one point in the sampled area. It can readily be seen that, of the three sampling cases just described, the sampling of new places on each day provides the greatest reduction of sampling errors and therefore the most reliable mean values.

Methods of sampling

Assuming that each component of variation is of substantial magnitude, the objective in sampling should be to reduce them both to a practical minimum with the least possible work. In the following examples are presented several methods of accomplishing this end; they are, of course, only suggestive, and may be varied to suit any particular problem. The first example is the simplest, while the other two are progressively more complex in design and supply more information on the factor studied. The first gives reliable data on total evaporation for a single area over each of several periods of time, with little information on individual daily values. The second provides the same periodic values, and adds information on variations in evaporation from day to day within each time-period. Finally, the third example furnishes just as much information as the second on periodic totals and individual storm values for net rainfall under a forest, and accomplishes this task for each of 20 separate areas, sampled simultaneously so as to estimate the magnitude of net rainfall on replicated plots subjected to several different timber-cutting treatments. The example given on the sampling of precipitation is an actual experiment in which the author was able to obtain results of satisfactory precision with about one-fifth of the work ordinarily required for this kind of study [1, 5].

All of the examples have several characteristics in common: (1) Both components of variation are important enough in magnitude to warrant thorough sampling; (2) each time-period for which a separate average or total figure is desired is subdivided into shorter units (as days or storms); (3) the whole sampled area, or each area for which a separate average is required, is stratified into a number of subareas equal to or a multiple of the number of time-units, within each of which random samples are taken to insure that all portions of the area are entered by samples; and (4) samples are taken in a separate areal stratum on each day (or other short time-unit), so that at the end of each time-period all strata have been sampled. (In these examples under (4), two samples are taken in each stratum. At least two are required for the estimation of sampling errors, and more may be taken if desired.) By this means a maximum number of places can be sampled with a minimum number of instruments, and an unbiased average of maximum precision is obtained for the desired period or periods of time.

Example 1--Object is to obtain a reliable estimate of evaporation from a large field, using a method such as Thornthwaite's [4]. The total evaporation for a 120-day season is to be estimated with maximum precision; 30-day totals are of somewhat smaller importance, and only an approxi-

mate value is desired for daily comparisons (see Example 2 for more precise daily figures). Recording instruments are employed; their relative lack of portability makes it desirable to leave each instrument in a single place for at least five days at a time.

Let each 30-day period be divided into six five-day intervals and the whole area into six subdivisions or areal strata of uniform size [for non-uniform strata, see 3], inside of any isolation-strip required to minimize border-effects. The purpose of areal stratification is to insure that every part of the area is entered by sampling observations. The number of strata should coincide with the number of five-day periods. For the first of the five-day periods, place two instruments at randomized locations in one stratum taken at random [without replacement; see 2, sec. 17.3]. Move the instruments to randomized locations in another stratum at the end of each five-day period, so that after 30 days all strata will have been sampled. Follow a similar procedure for each 30-day period, with new randomized locations taken for every sampling observation throughout the season and the areal strata sampled in newly randomized sequence. By this procedure the variations due to areal stratum and time are completely confounded within each 30-day period; that is, a comparison between any two five-day intervals will contain variations due to general position of the two measuring stations in the field as well as to time. Since short-period comparisons are not essential in this study, however, such confounding simply enhances sampling efficiency and comparisons between 30-day periods are obviously unconfounded.

As a result, for each 30 days a figure for total evaporation will be available, based on all days and on 12 positions in the field. By the end of the season 48 positions will have been sampled, with eight in each areal stratum. The error-variance due to time will be zero, and place-variation will have been minimized by stratification as well as by the number of locations sampled. Since the time-variance is zero, in this particular study the error-variance of periodic and seasonal totals can be computed directly from the differences between samples taken within each stratum and five-day period: a total of six differences per 30 days, with 24 differences (and degrees of freedom) for the whole season [3]. If only two fixed stations had been employed, a much less precise estimate of periodic and seasonal totals would have been obtained; the error-variances of the results would, on the average, have been six times as great for 30-day totals, and 24 times as great for the whole season.

For more intensive sampling the area may be divided into a greater number of strata and the instruments moved more frequently; or the strata may be increased to any desired multiple of six, and two or more strata sampled simultaneously in each five-day period. The latter procedure will, of course, require more instruments.

Example 2--Object is similar to Example 1, except that daily comparisons are desired. If variation from place to place in the field is not so large as to require a prohibitive number of instruments, this object may best be attained by the use of enough instruments, randomized over the field, to reduce the standard error of the resulting daily averages to a predetermined figure.

Ordinarily the cost of instruments and their operation would prohibit such detailed sampling. It may frequently be possible, however, to obtain a satisfactory amount of information on daily variations by providing a single measuring station at some fixed location in the field, in addition to the two perambulating stations suggested for Example 1. In all other features this technique is like the first example; the same stratified samples are obtained, providing the same total figures on periodic and seasonal evaporation.

The fixed station should be so located that trends from day to day will be as nearly typical of the field as possible, although the actual daily amount of evaporation need not represent the field.

With a season's data available for all three stations, a regression can be calculated to express the relation of daily evaporation at the two portable stations to that measured at the fixed station. Depending on the representative nature of the fixed station, this regression should be linear and fairly strong, and the value calculated for the dependent variable from any observed daily value at the fixed station should provide a reasonably accurate estimate of that day's evaporation on the whole field. The calculated evaporation may contain an unknown amount of bias associated with the failure of the fixed station to continuously retain its initial relation to evaporation on the field. If the fixed station is carefully located and operated, however, this bias should not be large. It should be noted, too, that the data from the fixed station are excluded from monthly or seasonal totals, which are therefore free from any possible bias.

Example 3--Object is to sample net rainfall in a forest and to compare it with gross rainfall for the purpose of estimating interception by mature pine on 20 plots, subjected to timber-cutting

treatments. In a study completed in 1941 [1, 5], the plots were arranged in four randomized blocks. In each block four of the five plots were cut-over in 1940, leaving one plot uncut and one each with a commercial reserve stand of 0, 2,000, 4,000, and 6,000 board-feet per acre. For this study only seasonal total values were desired, so that it was unnecessary to divide the whole season into shorter periods. Since it was essential to obtain unconfounded data for every plot, however, observations had to be taken simultaneously on each of the 20 areas.

In sampling net and gross rainfall, 24 sampling positions were located by randomization in each of the plots. For the first of 24 storms, a standard rain-gage was placed at each of two randomized positions for measuring net rainfall; two other gages were placed in the nearest available openings large enough to eliminate interception. After the first and each succeeding storm all four gages were moved to new positions, so that after 12 storms data on net and gross rainfall were available for all 24 positions in each plot. A second set of 12 storms permitted another complete circuit, ultimately providing 48 observations of net and gross rainfall on each of the plots. By this procedure the net and gross amounts of precipitation at any single sampling position were confounded with storm-size, although the variance associated with position within plots could be isolated by regression. Since samples were taken on every plot simultaneously, the total and average net and gross values per plot were free from any confounding.

As a result, the net rainfall under each cutting-treatment was accurate within limits of ± 0.01 inch for the average storm of 0.250 inch. In order to provide equal precision with gages at fixed locations, some 400 gages would have been required instead of the 80 which were actually employed.

In addition to the data on average and total net and gross rainfall it was possible to compute the amount of interception, to obtain accurate regressions of net rainfall per storm on gross, and from the regressions to calculate the expected net rainfall resulting from individual storms of various sizes under each cutting-treatment.

Summary

In the study of numerous environmental factors, especially those associated with climate, the research worker is often faced with the problem of adequately sampling the desired factor on relatively large land-areas; a task which is made difficult by the cost of the necessary instruments and of the collection and analysis of data. The problem may be considerably simplified by employing procedures which are outlined in this paper and summarized below.

(1) Stratify the whole time-period (season or year, for example) over which the sampling is to be distributed; divide the period into any desired sub-periods (time-strata) for which separate mean or total values are needed. Likewise, stratify the whole area into a number of areal strata, so as to insure that samples will be well distributed over the area. The number of areal strata should be equal to or a multiple of the number of days, storms, or short sampling-periods into which each time-stratum is divided.

(2) For each time-stratum, take two (or more, if desired) sample-observations at random within each areal stratum. A separate areal stratum may be sampled on each day or sampling period, so that only two instruments are required and that all areal strata will have been sampled by the end of each time-stratum. For more intensive sampling two or more areal strata may be sampled in each sampling period.

(3) If several different areas are to be compared with each other, the above process should be duplicated simultaneously on each area.

By this procedure a number of places can be sampled in each area under observation with a minimum number of instruments. Although the data for any single day or sampling period contain errors due to both time and sampling position, the total or average for each time-stratum and for a whole season are free from any confounding.

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DISCUSSION

A. E. BRANDT (Soil Conservation Service, Washington, D. C.)--In discussing this paper I am placed in the happy position of being able to commend the author highly on several points. First, he recognizes that environmental variation (which he has divided into two general classes on the basis of source and which can not be controlled by improved instruments, better trained personnel, or more advanced techniques) affects the precision of results though not, in an adequately designed experiment, their rigor. Second, he has selected techniques that have been developed and tested in other fields of experimentation which enable one to plan and conduct an experiment and analyze the results in such manner as to yield, in addition to the estimate of the mean value, an estimate of error which will permit sound conclusions to be drawn. Third, he has presented an efficient and relatively economical plan for securing sound estimates of precipitation related to areas of substantial size. And fourth, he has not felt that it was necessary to change the language generally used for the selected techniques in the field in which they were developed.

In one place the author says, parenthetically, ". . . ($\bar{x}$ being the mean of the observed sample value and s^2 their variance), . . ." This may lead to some confusion and needless criticism for some people, notably Egon Pearson and J. Neyman, distinguish between the variance of the observed sample-values and the estimate of the population-variance based on these sample values. This possibility of confusion can be eliminated easily by changing the expression to read ". . . ($\bar{x}$ being the mean of the observed sample-values), ..."

Personally, I am somewhat disturbed because the author has not once referred to the original source of the experimental design he has applied. This is, of course, no handicap to those familiar with the field but, it seems to me, a very serious one to anyone who wishes to pursue these techniques and explore further applications of them.

THE SUN'S SPOTTEDNESS AS A POSSIBLE FACTOR IN TERRESTRIAL PRESSURE

I. I. Schell

(Abstract)

The occurrence in the late 1930's of a period of maximum sunspot-activity surpassing greatly in intensity the maxima in the past 60 odd years, coupled with the present availability of a homogeneous series of data from a fairly wide network of stations, stimulates a reexamination of the question of sunspot-pressure relationships and a consideration of the problem on a broader basis.

Assuming that the Sun's spottedness may modify the terrestrial pressure-distribution but only during periods of extremely weak or extremely strong sunspot-activity (the effect of moderately strong or weak activity being insufficient measurably to disturb a given phase of the circulation in which the atmosphere may be), an index of sunspot-activity based on the persistence of very high sunspot-activity (no less than three consecutive months with sunspot-number equal or in excess of 80.0) and on the persistence of very low sunspot-activity (no less than three consecutive months with sunspot-number equal or in defect of 5.0) was derived. The strongest and weakest periods of sunspot-activity that occurred in the past 60 odd years were taken as plus and minus unity, respectively. The periods of very high and very low spottedness represented by their sunspot-index values were then compared with the pressures in the low and high-latitude zones, the results showing relatively low pressure in the low-latitude zone and high pressure in the high-latitude zone during periods of high sunspot-activity, and a relatively high pressure in the low-latitude and low pressure in the high-latitude zones during periods of very low sunspot-activity. Furthermore, the greatest negative difference (low-latitude minus high-latitude zones) in pressure-deviation during the period examined (for which adequate meteorological data were available) was associated with the highest value of the positive sunspot-index (very strong sunspot-activity), and, conversely, the biggest positive pressure-difference (low-latitude minus high-latitude zones) coincided with the

biggest value of the negative sunspot-index (very weak sunspot-activity).

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INTER-AMERICAN PROGRAM FOR TRAINING IN METEOROLOGY

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The remarkable advance made in the science of meteorology since World War No. 1 was made possible by the rapid development of aviation. With this development, increasing demands for greater frequency, accuracy, and coverage of weather information have resulted in increased budgets for meteorological work.

Countries in which transportation by air has increased have benefited proportionately in their meteorological development, as evidenced most forcefully in Europe and North America. In South and Central America, however, the increase in flying, while considerable, has not attained the same proportions as in the regions before mentioned and, as a consequence, meteorological advances have been somewhat less marked. Following the conferences at Rio de Janeiro in 1935, at Lima in 1937, and at Montevideo in 1939, a very definite impetus was given to South American meteorology in general, and to the standardization, codification, and exchange of current weather-observations in particular. Following these meetings the need for well-organized instruction in meteorological work and theory became more fully realized. Most all instruction is perforce of the in-service training type, few if any of the universities being in a position to support courses in advanced meteorology for which there had been relatively little demand.

Having in mind the beneficial results obtained in the United States following the introduction of meteorological courses in some of the universities and in order to stimulate and broaden the interest in meteorological instruction already noted in Latin-American countries, plans were formulated in the late summer of 1942 to sponsor for Latin-American students a course at the observer-level dealing largely with observational work and technique. This plan included also instruction in basic meteorological principles and their application to the practical problems of forecasting. At the same time it was proposed to provide sufficient instruction in the English language so that students, who might have an opportunity later to attend universities in this country, would not be handicapped by unfamiliarity with the language.

To minimize the transportation and housing problems, it was decided to select for the school a more or less central location with respect to the countries of Latin America. As a result Colombia was chosen and the Government of that Republic, upon request of the State Department, was kind enough to accord the privilege of conducting the course at Medellín. This city, with a population of about 180,000, an elevation of slightly less than 5,000 feet, and a delightful climate, provides an ideal location for the project.

Funds for the conduct of the school were provided jointly by the Office of the Coordinator of Inter-American Affairs and the Defense Supplies Corporation, with the understanding that the Weather Bureau would administer the project.

To assist in selecting candidates, examinations of the multiple-choice type were prepared by the Civil Service Commission and translated into Spanish, Portuguese, and French. The examinations were organized into four groups: (1) Mathematics and physics; (2) English language; (3) language-aptitude; and (4) science-aptitude. Examinations were conducted in the different countries under the supervision of the Embassies, Consulates, and coordinating committees. Each applicant was interviewed personally. Final selections were made on the basis of educational qualifications, the interviews, and the results of the four examinations.

The class, which opened formally on February 22, 1943, with many high public officials in attendance, will continue for a period of about six months. It numbers 200 students, every one of the Latin-American Republics being represented. There are eight American instructors--four technical and four language. In addition, at the request of the Weather Bureau, eight Latin-American technical instructors were designated by Argentina, Brazil, Chile, Costa Rica, Ecuador, Guatemala,

and Uruguay--these Latin-American instructors form a very essential and important part of the faculty.

Experience in connection with the Hurricane Training Class, conducted in 1942 at New Orleans for students from countries surrounding the Caribbean Sea, as well as in the present project at Medellín, emphasizes the great need for meteorological texts published in Spanish and Portuguese. The Weather Bureau, in connection with these two projects, has found means to translate into Spanish several articles, books, and pamphlets amounting to some 800 typewritten pages. It is understood that there is being projected a plan to translate one or more of the standard textbooks on meteorology into Spanish and Portuguese. More work of this kind is sorely needed and will be greatly appreciated by students in Latin America.

U. S. Weather Bureau,
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AMERICAN GEOPHYSICAL UNION

TWENTY-FOURTH ANNUAL MEETING

SECTION OF TERRESTRIAL MAGNETISM AND ELECTRICITY

REPORTS AND PAPERS

Washington, D. C.
April 23, 1943

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THE STUDY OF THE EARLY HISTORY OF TERRESTRIAL MAGNETISM

H. D. Harradon

In order to furnish a background for our present knowledge of terrestrial magnetism, many eminent scholars have devoted much time and labor to the examination of ancient and medieval documents containing references to the magnet and its properties. Such studies involve the expenditure of much patience because the original documents are not readily accessible since they are widely scattered in libraries and collections. Difficulties are also encountered in understanding them, because they are usually written in language now not easily intelligible even to those who speak the modern forms of the languages represented. Parchment and other materials on which these manuscripts were written were, during the middle ages, so scarce and expensive that the urge for economy led to the excessive employment of arbitrary abbreviations which, often dimmed by the effects of time, render the text difficult to decipher. Expressions, too, employed before modern physical concepts came into use, make doubtful the interpretation of many passages.

The modern student of geomagnetism is, in general, more concerned with the mastery of modern techniques and theoretical investigations than with the study of early writings which record the first steps in the path towards our present knowledge. Yet the study of the historical development of the science is not without interest and its cultural value is considerable. It reminds us how painfully slow was early progress in arriving at the elementary truths on which the modern structure of magnetic knowledge has been erected.

Although a comprehensive history of geomagnetism has never been written, many important contributions to the subject have been made. Among the most recent are the chapters by A. Crichton Mitchell [see 1 of "References" at end of paper] who, on the basis of the study of original sources, discussed the controversial questions pertaining to the discovery of the directive property of the magnet in the Earth's field, the origin of the nautical compass, and the discovery of the magnetic declination and inclination. He rejects the claim of the Chinese as the first discoverers of the compass on the basis of the much-quoted story of south-pointing carts and holds that the earliest reliable evidence of Chinese knowledge of magnet pointing north and south is to be sought late in the eleventh century A.D.

Extensive study of the classics of Greece and Rome has revealed no knowledge concerning the polarity of the magnet or its directive force. There are, however, many references to its attraction for iron, some of which are not without interest, as, for example, the following from Lucian (about 125-190 A.D.): "If this girl look at you, what way would there be to get away from her. For she would throw a noose around you and drag you off wherever she wished just as the Heraclean stone (that is, lodestone) does to iron" [2].

Thus it is not until medieval times that important papers dealing with the polarity and directive force of the magnet are encountered. In view of their inaccessibility, the late G. Hellmann was led to reproduce some of the more important in his "Rara Magnetica" [3]. These reproductions are partly in facsimile and among them six different languages are represented. Although one is grateful for this remarkable service which Hellmann has performed for geomagneticians, few of the latter would be able to read them all, and most would have difficulty in reading any in a language other than their own.

In order to make these outstanding contributions more widely known and more generally useful, Professor Sydney Chapman, who himself has taken no small interest in the history of geomagnetism, suggested to the Editor of the Journal of Terrestrial Magnetism and Atmospheric Electricity that it would be a new and useful departure to include from time to time in its pages historical articles and reproductions of the old classics, either in the original languages or in translation. "The inclusion" he said "of these old writings, in a continuing publication, would also increase the chance of their coming to the notice of future readers, particularly in view of the general and very proper desire of librarians to have complete sets of the periodicals current in their collections." In accordance with Chapman's suggestion, several of these contributions have already been published in volume 48 of the Journal for 1943 [4].

The first of these is an English translation of the famous Latin letter of Petrus Peregrinus de Maricourt to Sygerus de Foucaucourt on the magnet, written in 1269, while in camp at the siege of

Lucera, in Apulia, southern Italy. According to Hellmann, this letter is the oldest occidental treatise on magnetism and at the same time one of the earliest evidences of the beginning of experimental investigation in the Middle Ages. In the translation a literal rendering rather than a paraphrase has been attempted, in order that something of the author's intimate style might be preserved.

Translations of other papers which mark important advances in magnetic science in medieval times are in preparation.

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EVALUATION AND INTERPRETATION OF THE COLUMNAR RESISTANCE OF THE ATMOSPHERE

O. H. Gish

(Abstract)

The electrical resistance of a vertical column of air of one cm^2 cross-sectional area and extending from the Earth's surface to a specified altitude is a concept which facilitates the discussion and interpretation of some aspects of atmospheric electricity. The author uses the term "columnar resistance" of the atmosphere to denote this concept. The columnar resistance may be defined either as the integral, along the vertical, of the air-resistivity from the Earth's surface to a specified altitude, or as the quotient of the potential, relative to Earth, at a specified altitude, by the vertical electrical conduction-current in the atmosphere.

Estimates of columnar resistance have been made, in accordance with the latter definition, by using measurements made on balloon flights of the potential-gradient along the vertical to determine the potential at a given altitude and employing observed values of the vertical conduction-current. Estimates in accordance with the first definition have been made in two ways: (a) Values of observed air-resistivity (the reciprocal of air-conductivity, the actual measured element) were integrated over the altitude-range of the observations (greatest altitude 22 km) [see 1 of "References" at end of paper]; (b) calculated values of air-resistivity, based on measurements of cosmic radiation and on representative meteorological data, were integrated up to an altitude of 25 km [2].

The relative columnar resistance is also of interest in a number of cases. If R_1 and R_2 and i_1 and i_2 denote the columnar resistances and vertical conduction-currents, respectively, at two stations, then the relative columnar resistance at station No. 1 is (R_1/R_2) and this is taken equal to (i_2/i_1). (Here and elsewhere, if altitude is not specified, R denotes the resistance of a column extending from the Earth to an indefinite altitude.)

The assumptions upon which the several methods of determining columnar resistance and the application of this concept in interpretation depend, are examined in the full report. The circumstances in which these assumptions are justified and the reliability of estimates of columnar resistance thus far made by the different methods are also discussed.

The estimates of columnar resistance for similar circumstances by the different methods differ less than was initially expected and for open country lie between 7 and 10 in units of 10^{20} ohms--over the environs of some cities, values as great as five times these are indicated.

Comparisons of the measured values of the vertical electrical conduction-current near sea-level on land with those for open ocean [3,4] indicate that the average columnar resistance is probably always greater for the former than for the latter. Apparent exceptions to this will appear if the dependence of columnar resistance upon latitude is not taken into account. Such a case is cited.

Tentative interpretations of the apparent variation of the relative columnar resistance, either variation with time or with position, made at various times, are reexamined and some alternative interpretations are suggested.

All interpretations attribute the changes in columnar resistance chiefly to changes of either the concentration or the vertical distribution, or both, of the nuclei of condensation in the lower atmosphere. Heretofore simple arbitrary forms of distribution were assumed, if the quantitative examination of data was pushed that far. In the present investigation, forms of distribution were sought which are consistent with the atmospheric-electric and meteorological observations and which conform with the dynamics of the atmosphere and other factors which probably prevailed in the region during the period of observation.

These tentative interpretations constitute the first plausible quantitative explanation of some of the changes in columnar resistance.

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[4] G. R. Wait, Terr. Mag., v. 47, pp. 243-249, 1942.

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CAUSE FOR THE RADICAL CHANGE WITH SEASON IN THE TYPE OF POTENTIAL-GRADIENT DIURNAL-VARIATION CURVES AT WATHEROO

G. R. Wait

(Abstract)

The atmospheric potential-gradient over the oceans was found by Mauchly [see 1 of "References" at end of paper] to vary systematically through the day. The variation is, however, unlike that of temperature, which is a function of local time. Instead, the variation in potential-gradient depends upon universal time, that is, at the instant it passes through a maximum or minimum at one place on the globe it likewise passes through a maximum or minimum at all other points as well. Over land, however, this is not the case. The variations at some stations are in step with those over the oceans while at other stations they may never be in step and at still other stations the variations may be in step during only a portion of the year. A daily variation in the potential-gradient is to be expected at all stations over land or over sea due to the fact that the magnitude of charge on the Earth, caused presumably by the action of thunder-storms, does not remain constant through the day but varies in a systematic manner. Whether the variations follow universal time or not depends upon the behavior of the resistance of the atmosphere to the air-earth current which flows between the ground and upper air. The variations in potential-gradient will follow universal time when the resistance of the lower stratum of air varies through the day as that of the entire vertical column of the atmosphere over the station. Over the oceans the resistance of the lower stratum of air, as well as that of the entire vertical air-column, remains essentially constant through the day. As a result, the variation in potential-gradient is independent of local time and follows universal time.

At the Watheroo Magnetic Observatory (Western Australia) the resistance of neither the lower stratum of air nor that of the entire vertical air-column is constant through the day. [See 2.] During the summer the two resistances vary in a similar manner, and consequently the variation in potential-gradient is similar to that over the oceans. On days when there is considerable smoke in the air from nearby bush-fires, the potential-gradient is greatly disturbed. The similarity between the potential-gradient variation at Watheroo and over the oceans is not, as one might readily expect, diminished but is actually increased. This is because the smoke is uniformly distributed vertically and affects the resistance of the lower stratum of air to the same relative extent as it does that of the entire vertical air-column. During the winter, on the other hand, the similarity between potential-gradient variation at Watheroo and over sea is not marked (see Fig. 1). The var-

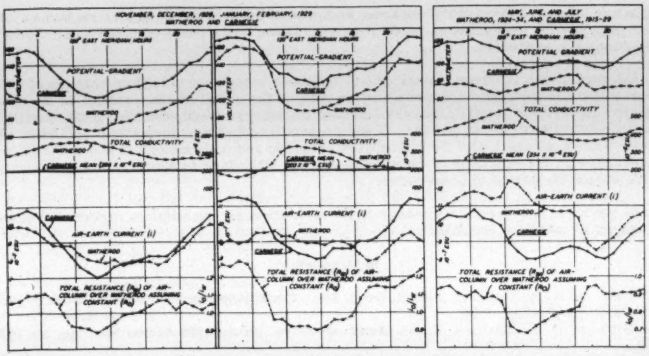

Fig. 1--Diurnal variation of atmospheric-electric elements at Watheroo and over the ocean

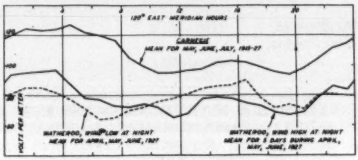
CARNEGIE
MEAN FOR MAY, JUNE, JULY, 1915-27
WATHEROO, WIND LOW AT NIGHT
MEAN FOR APRIL, MAY, JUNE, 1927
WATHEROO, WIND HIGH AT NIGHT
MEAN FOR 5 DAYS DURING APRIL, MAY, JUNE, 1927

Fig. 2--Comparison of values of potential-gradient, Carnegie and Watheroo

iation in resistance of the lower stratum of air is dissimilar to that of the whole vertical air-column. This dissimilarity, for the most part, is brought about through the action of radium and its products which have escaped into the lower stratum from the ground (see Fig. 2). During times of calm the dissimilarity is increased since the radioactive matter can then accumulate in the air. During times with considerable wind the similarity is increased, for then the radioactive matter is mixed with the upper layers of air and the variation in resistance of the lower stratum of air closely follows those of the entire vertical air-column. Radioactive matter escapes into the air during the summer and winter, but its effectiveness in summer is diminished through the presence of considerable smoke from nearby bush-fires.

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THE ELECTRODE-EFFECT IN THE ATMOSPHERE

K. L. Sherman

The theory of the electrode-effect in the atmosphere has been gradually developed over a period of years. Those published accounts of theories with which the author is acquainted are based on comparatively simple assumptions. For example, turbulence is neglected and it is assumed that the number of condensation-nuclei and the rate of production of small ions do not vary with height. A more complete treatment embodying these and other complicating assumptions is needed but would apparently be very difficult to develop. Although it now appears quite feasible to work out the theory for other distributions of nuclei and rate of production of small ions, the quantitative effect of turbulence does not appear to be so easily incorporated--probably because it is thought the conditions are usually so complicated at a particular location that the simple theory is inapplicable, and probably also because of its complexity, even for the simple case, the theory has not generally been adopted. The results obtained at College, Alaska, during the International Polar Year [see 1 and 2 of "References" at end of paper], however, showed remarkable agreement with the theory, suggesting that the underlying assumptions were sufficiently fulfilled at that place during much of the time. With these results as a stimulus, examination of the records from other locations has shown that the electrode-effect is generally more important than has been assumed.

One of the ways in which the electrode-effect normally manifests itself in the atmosphere is by a depletion of the negative ions from the air near the Earth's surface in the positive potential-gradient. According to the theory, the amount of depletion of the negative ions and any increase or decrease in the number of positive ions depends on the ratio of the combination-coefficient pertaining to small ions and nuclei to the mobility of the small ion. For example, using the subscript ∞ to denote conditions in a weak field and 0 that in a strong field, the ratio of the number of positive ions in a weak field to that in a strong positive field would be given by $(n_\infty/n_0) = [a^{1/(a-1)}/2]$, where $a = (\eta/4\pi ek)$, η being the combination-coefficient appropriate for the attachment of small and large ions or nuclei, k is the mobility of the small ion, and e is the unit-charge. Thus, if the electrode-effect theory is valid, by examining the relative change in number of positive and negative small ions with changes in the field, an estimate of the combination-coefficient can be obtained in terms of the mobility. Upon examination of the above relation, it will be seen that if a has a value of two, the concentration of positive small ions is not affected ($n_\infty = n_0$) by changes in the positive gradient. As a increases, the ratio (n_∞/n_0) approaches one-half as a limit. It is interesting to note that this is the limit also found by equating the current at the surface, where the field is large, to the current at some height in a weaker field. Using this assumption $i_0 = E_0 n_0 ek = i_\infty = 2\, E_\infty n_\infty ek$, where i refers to the air-earth current and E to the potential-gradient. If there is any positive space-charge present, the minimum value of (E_0/E_∞) is unity and the minimum value of (n_∞/n_0) is one-half.

Gish and Sherman [3] have summarized and discussed the values so far advanced for the values of the combination-coefficients. It is evident that these are either quite variable from place to place and under different circumstances or that the values have not been determined with precision. In any event, it seems important to obtain any additional information possible regarding the value of these coefficients at still other locations and under conditions as they exist in the atmosphere. This information is particularly needed at observatories which continually record atmospheric-electric elements. The author is aware that the assumptions made in the development of the simple theory make it necessary to use caution in interpreting comparisons with observations. Still, with some success proven in comparing the theory with observed results and with the need for further indications of the value of the combination-coefficient in mind, it seemed desirable to point out the possibility of using records of positive and negative conductivity and of potential-gradient obtained at observatories, where data are regularly recorded, to obtain an estimate of the coefficient and to present preliminary values based on the initial examination of such records.

Typical records of the behavior of the air-conductivities at times of large potential-gradient have been published [4, Figs. 13 and 15]. Although the gradient is not always recorded during times of extreme values, its sign may be determined by noting the sign of the conductivity which shows the most marked decrease. (Negative conductivity is decreased nearly to zero by high positive potential-gradients.) It is seen in these illustrations that the ions of opposite sign are but little affected by the gradient. As indicated above, no effect would be expected if $\eta = 8\pi ek$. This corresponds to a value of 5.4×10^{-6} cc/sec for η if k is taken to be 1.5 cm/sec/volt/cm. This value is about that indicated by the most reliable determinations [see 3]. Examination of records from the Huancayo, Watheroo, and Tucson Magnetic Observatories, in addition to those published, do not indicate large variations in η and the values do not differ markedly from 5.4×10^{-6} cc/sec. If

more exact estimates are to be obtained by this method at places where other values of the coefficient are indicated, it would likely be necessary to obtain records of potential-gradient with a less sensitive recorder at times when large fields occur.

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[4] O. H. Gish, Nation. Res. Council, Physics of the Earth, v. 8, Terrestrial magnetism and electricity, pp. 149-230, New York, McGraw-Hill Book Co., 1939.

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ON SPONTANEOUS INCREASE OF MAGNETIC MOMENTS

H. Herbert Howe

Background--It has long been considered axiomatic that magnets gradually lose strength, and the only question has been how to make the loss as slow as possible. Since it requires the expenditure of energy to produce a magnet, it would appear that the only possible spontaneous change would be for the magnetic moment to decrease. The discussions of magnets in standard reference works appear to fall into two classes: (a) Those which say that the moment slowly decreases; (b) those which assume that everyone knows this and merely discuss methods of making the decrease as slow as possible.

There are a few published references to an increase for a short time after magnetization, but references to long-continued increase are few indeed. One such reference is found in what may have been the last publication of the late Dr. la Cour [see Reference 1 at end of paper], in which he states: "Up to now the magnetic moment of several of the field magnets has shown a tendency to increase in the course of time--some of them by up to 0.01 per cent per month. It is obvious that such increase cannot continue forever at the same rate, and it seems likely that the increase is due to some deficiency, as yet undetected, in the manufacturing method of these magnets. Investigations are being made with the object of eliminating the increase or shortening the time during which such increase goes on, but these investigations require rather long time."

In view of the fact that so little is known on this subject, it seems desirable to publish a summary of the experience of the United States Coast and Geodetic Survey with such magnets. This behavior was first noticed a number of years ago by George Hartnell. The magnet in that instance was used as a scale-value deflector, so that the resulting moments were not very accurately determined.

History of Magnet 31LC--In 1937 the stirrup of C. and G. S. magnetometer 31 (Cooke pattern) broke, and in repairing it the instrument was thoroughly overhauled. This included making a new pair of magnets of 36 per cent cobalt steel. The new long magnet is distinguished from the old by calling it magnet 31LC.

In March 1939, H. E. McComb and J. W. Joyce took this magnetometer on a field-trip, in which a number of new instruments were tested. The magnetometer was then unused until the fall of 1940, when it was sent to Tucson, where it has been used since as the standard magnetometer of the Observatory.

The observations preparatory to sending it to Tucson gave the unexpected result that the magnetic moment had increased nearly one-half per cent since March 1939. This was far more than the error of determination. The moment has continued to increase during the 2-1/2 years the instrument has been used at Tucson.

Present data--The magnetic moment of a magnet is a function of temperature. In the previous section, reference is made to the moment after it has been corrected for temperature, by adding 0.00008 to log M for each degree that the temperature exceeds 20°C. This value of M is designated as M_{20}.

It is to be noted that the constancy of the magnetic moment does not enter critically into the results of observations with a magnetometer. It is only necessary that M_{20} remain constant during a set of observations. However, the moment is regularly reduced to 20° and tabulated, so that a study can be made to locate possible abrupt jumps in the moment, which might be correlated with sudden changes in some other property.

Since 1940, two sets of horizontal intensity (H) have been made in nearly every week. No correction is applied for change of H during a set, but the method of observing is such that a linear change of H cancels out. A set involves the timing of 20 (overlapping) groups of 100 oscillations of the long magnet, and the measurement of 16 deflections of the short magnet, half at each of two distances.

To make the rate of increase of magnetic moment more apparent, the author had made a graph showing log M_{20} and temperature against time, the temperature being plotted to see if there were any correlation between the curves, which would indicate an erroneous temperature-coefficient. There was no correlation, but nevertheless there was a definite relation: The increase in moment occurs during the summer, but not during the winter. This will be seen in Figure 1, in which each circle usually represents two sets (often with quite different temperatures).

This unexpected phenomenon was discovered independently by James H. Nelson, Observer-in-Charge of the Tucson Magnetic Observatory. Figure 2 is reproduced from a graph prepared by

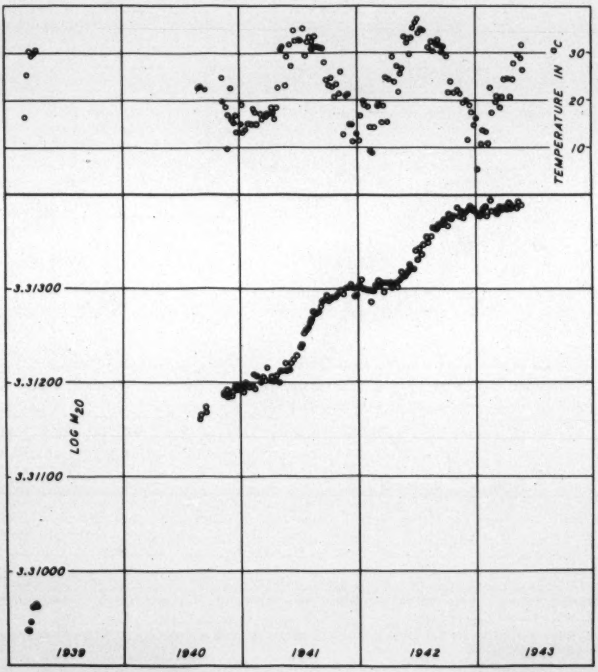

Fig. 1--Log M (reduced to 20°C) and temperature for magnet 31LC

him. He also plotted a curve showing log M_{20} with a linear increase of 0.00092 per year removed. This he called "Log M_{20} adjusted"

Nelson drew several conclusions from this curve. First, there is apparently no correlation between the adjusted log M_{20} and temperature (that is, the adopted temperature-coefficient is essentially correct). Second, if the temperature and adjusted log M_{20} be regarded as sine-curves, they are approximately 90° out of phase.

Let us examine the consequences if this last approximation were exactly true. Let T = temperature; t = time from a definite but unstated zero-point; L = log M_{20}; A, B, C, etc. = constants. The approximation is that

$$T = A + B \sin Ct \quad (1)$$

$$L = E + F t + G \cos Ct \quad (2)$$

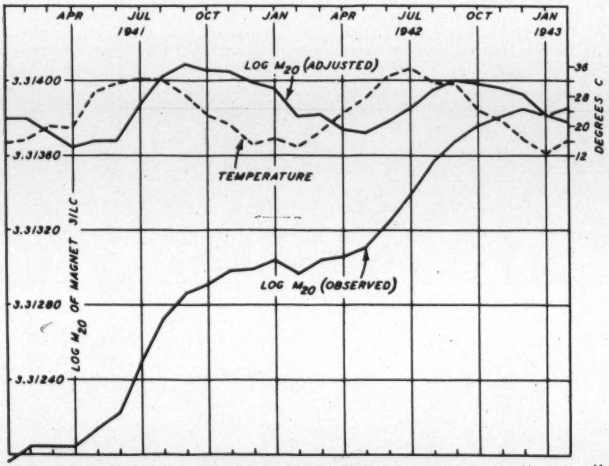

Fig. 2--Fluctuations of log M_{20}; a linear drift was removed to derive "adjusted" values (courtesy James H. Nelson)

the term Ft being the difference between log M_{20} and adjusted log M_{20}. C appears in both equations because the length of the cycle is one year in each. Differentiating the second equation with respect to time: $(dL/dt) = F - GC \sin Ct = F + (GCA/B) - (GCT/B)$. That is, the rate of change of log M_{20} is a linear function of temperature.

Next, suppose that Nelson's curves were sine-waves but differing in phase by something other than 90°. This would require adding to (2) a sine-term, that is, a term that is a linear function of temperature. That would merely mean an error in the temperature-coefficient.

Next, we see that the fact that the curves are not exactly sine-waves does not disprove the hypothesis that the rate of change of log M_{20} is a linear function of temperature. For even if it were exactly true, erratic fluctuations of T would cause erratic fluctuations of the adjusted log M_{20} with no evident relation between the two curves. A more accurate investigation of this proposed law was made as follows:

For each month, the mean date of observation and the mean value of log M_{20} were computed.

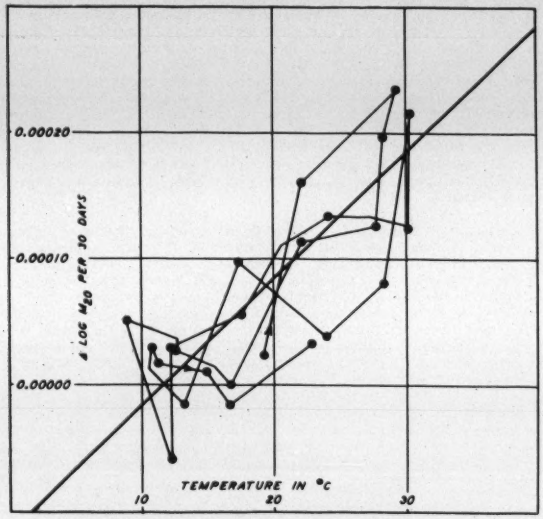

Fig. 3--Differences of consecutive monthly means of log M_{20}, reduced to 30-day intervals, against mean temperature for corresponding intervals (observer, James H. Nelson)

(In order to make the results more homogeneous, only observations by Nelson were used, he being the more experienced of the two observers.) The differences between consecutive values were taken, giving increase of log M_{20} for a specified number of days. The quotient of these numbers was multiplied by 30 to give the increase of log M_{20} per 30 days. These quantities are the ordinates of Figure 3.

There is uncertainty as to what temperature should be used as abscissa. Presumably, it should be the average temperature between the mean dates used in deriving the ordinates. (According to the proposed law, the mean increase over any interval can be derived by using the mean temperature; this is not the case if the rate of increase is not a linear function of temperature.) This would be different from the temperature at the time of observation, which is used in Figures 1 and 2.

It was decided to use the mean of the daily maxima and minima shown by the thermometers operated at the Observatory on behalf of the United States Weather Bureau. These temperatures may not be representative of the temperatures to which the magnet is actually subjected, since it is kept between observations in a closed, uninsulated building, in which the temperature on sunny days is apt to be considerably higher than in the ventilated shelter used by the Weather Bureau. However, it is hoped that the fluctuations from month to month observed for the Weather Bureau may be reasonably representative of the fluctuations to which the magnet is subjected.

Consecutive points in Figure 3 have been connected by light lines in case it is desired to study any "drift" through the interval covered. The heavy line representing the mean slope gives the equation

$$\text{Change of log } M_{20} \text{ per 30 days} = T - 11.5$$

where the logarithm is expressed in units of the fifth decimal place, and T is the Centigrade temperature.

There is no way of telling whether the scatter of the points is due to experimental causes (difficulty of measuring the moment with sufficient accuracy, and uncertainty of the mean temperature between observations) or to the action of influences other than the assumed relation.

Physical explanation--We return now to the question of how it is possible for the moment of a magnet to increase spontaneously. According to elementary principles, energy must be added to a magnet to magnetize it, and increasing its moment should require additional energy.

From the data presented above, it is seen that, at least for this particular magnet, the increase of moment is more rapid when the temperature is high. This fact, however, does not seriously restrict the possible mechanism, because the rate of many chemical and physical reactions depends upon the temperature.

Several suggestions have been made: (1) That there is a redistribution of magnetism, of such a nature that the magnetic moment (which is a measure of the field at a large distance from the magnet) increases without addition of energy. This seems unlikely, however, because there would probably be a substantial difference in the values of M and H derived from deflections at two distances, which does not, in fact, exist. (2) That the energy comes from some other form of molecular or atomic energy, involving a rearrangement of the elementary magnets of which the magnet is composed. (3) A new suggestion, made by the present writer, is the following: It is known that the moment decreases when the temperature rises, and vice versa. Perhaps the increase and decrease are not exactly equal, the daily rise exceeding the fall. The energy would then come from external thermal energy. It appears that this would not contravene the second law of thermodynamics.

This third suggestion differs fundamentally from the other two in that it makes the rate of increase depend upon the temperature-range, as well as the mean temperature. The data at hand are apparently not sufficient to determine whether such is the case, because the mean range is roughly the same from month to month.

Proposed research--In the paragraph quoted above, la Cour points out that the long time required hampers research aimed at determining how to make magnets that will not exhibit this phenomenon. The difficulty of making magnets that will surely exhibit it, in turn, hampers any research into the physical causes underlying it. If such magnets could be obtained as desired, there are two lines of research that would give useful information on the subject:

(a) Test the third proposed cause by keeping a magnet in a well-insulated room between observations, to eliminate the daily rise and fall of temperature, while permitting the seasonal change. Comparison of the behavior of such magnets with control-magnets left exposed to the usual fluctuations would show whether the increase is due to the daily rise and fall of temperature, or merely to the average high temperature.

(b) Keep a magnet for a considerable time at a constant temperature; then for a considerable time at another temperature, etc., to test whether the rate of increase is really a linear function of temperature. The lowest temperature could readily be that of dry ice (CO_2).

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MAGNETIC WORK OF THE UNITED STATES COAST AND GEODETIC SURVEY FROM APRIL 1942 THROUGH MARCH 1943

O. W. Swainson

Geomagnetism is playing an important role in the war as it is essential for nautical and aeronautical navigation, especially in military zones where radio beacons, lights, and fog-signals have been discontinued. It is used in field-maneuvers, gun-firing, magnetic mines, protection from such mines, and for many confidential purposes. Consequently, the United States Coast and Geodetic Survey devoted most of its work in the office and field during the past year to gathering,

processing, and compiling information for the military authorities.

Close cooperation has been continued with the Department of Terrestrial Magnetism, Carnegie Institution of Washington. The Institution loaned instruments and furnished data which enabled the Coast and Geodetic Survey to carry out many projects that otherwise could not have been done.

Magnetic surveys

The magnetic surveys begun in the area of the Caribbean Sea were continued through June 1942. This work was done in cooperation with the State Department and the American Republics. It replaced the usual ten-year periodic survey by the Department of Terrestrial Magnetism, Carnegie Institution of Washington, as that Institution was engaged in other work to the limit of its capacity. Stations were occupied in Cuba, Haiti, Dominican Republic, Puerto Rico, Venezuela, Colombia, Panama, Costa Rica, Nicaragua, Honduras, El Salvador, Guatemala, Mexico, and several of the smaller Caribbean islands. From the data gathered, a new isogonic and isoporic chart of the Caribbean Sea area has been prepared, and is in the hands of the printer. The methods representing the isogonic and isoporic lines on this chart has been adopted as standard practice for the future.

The work in the American Republics was again taken up in October 1942 and is still in progress. The project provides for occupying stations in Venezuela, Colombia, Ecuador, Peru, Bolivia, Chile, Argentina, Uruguay, Paraguay, and Brazil. The observations in the first six countries have been completed. In Chile, the observers progressed as far south as Punta Arenas on the Straits of Magellan. In Brazil, the program provides for observations in the Amazon valley as far west as Benjamin Constant on the Peruvian frontier, and Porto Velho near the Bolivian frontier. Instrumental comparison-observations are scheduled for the magnetic observatories at Huancayo (Peru), Cordoba (Argentina), and Vassouras (Brazil). The program also includes diurnal-variation observations for both declination and horizontal intensity in the vicinity of the magnetic equator at stations located between the northeastern coast of Brazil and the coasts of Peru and Chile.

In the United States, field-observations were made in the extreme western and southwestern States from June through October 1942. Search was made for anomalies in declination reported by pilots along airways in the States of Minnesota, Iowa, South Dakota, and Washington. Observations for declination at airports have been included in the program of six field-parties engaged upon making special surveys of airports in all sections of the United States. Scattered observations were also made in Alaska. At the present time, observations are in progress in North Carolina.

Table 1 lists the observations made during the past year.

Office-work

Magnetic data were furnished to nearly every mapping service in the Government, including the Army Map Service, Army Signal Corps, Army Air Forces, Geological Survey, Forest Service, Soil Conservation Service, and Bureau of Agricultural Economics.

Seven volumes of results at observatories have been prepared for publication. These volumes are Magnetic observatory results at Sitka for 1931-32, Cheltenham for 1931-32, Honolulu for 1931-32, Tucson for 1931-32, Sitka for 1933-34, Honolulu for 1933-34, and Tucson for 1933-34.

The Alaska magnetic tables and magnetic charts for 1940 have been prepared for the printer. A revised edition of the publication "The Earth's magnetism" has been about completed.

Directions have been prepared for testing compass-roses and compass-rose sites for artificial disturbances. It is hoped these directions will facilitate the adoption of standard procedure in the establishment of compass-roses at airports.

Broadcasting of the three-hour-range indices, K, was discontinued, but the figures were furnished to the Department of Terrestrial Magnetism of the Carnegie Institution of Washington and to other authorities.

The Work Projects Administration Office maintained in New York City continued to process special observatory results until the end of June 1942, when the project closed. Work in New York was resumed about July 8, 1942, with a smaller force of civil-service personnel. A similar project of the Work Projects Administration in San Juan, Puerto Rico, worked on that Observatory's records.

Table 1--Magnetic stations occupied April 1942 to March 1943

State or region	Repeat-stations				Other stations	Totals
	Old		New			
	D only	Complete	D only	Complete		
Arizona	...	1	3	1	4	9
California	...	1	...	2	14	17
Connecticut	...	...	...	...	1	1
Delaware	...	...	...	...	1	1
Florida	...	...	...	...	10	10
Idaho	...	1	...	...	...	1
Illinois	...	...	...	...	5	5
Indiana	...	...	...	...	1	1
Iowa	...	...	...	...	2	2
Kansas	...	...	...	...	1	1
Louisiana	...	...	...	...	1	1
Maine	...	...	...	...	10	10
Massachusetts	...	...	...	...	1	1
Minnesota	...	...	...	...	4	4
Mississippi	...	...	...	...	2	2
Nebraska	...	...	...	...	1	1
Nevada	...	...	...	...	2	2
New Hampshire	...	...	...	...	1	1
New Mexico	...	3	2	4	...	9
New York	...	...	...	...	6	6
North Carolina	...	...	...	...	3	3
North Dakota	...	...	...	...	1	1
Oregon	...	...	2	...	7	9
Pennsylvania	...	...	...	...	1	1
Rhode Island	...	...	...	...	2	2
South Carolina	...	...	...	...	2	2
Texas	...	...	...	...	4	4
Vermont	...	...	...	...	1	1
Washington	1	1	...	6	18	26
Wisconsin	...	...	...	...	1	1
Alaska	...	1	...	...	19	20
Bermuda	1	2	...	...	5	8
Mexico	...	1	...	2	...	3
Central America	...	8	1	8	...	17
West Indies	...	1	...	1	2	4

Instrumental work

In cooperation with the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, a modification of a special Z-type magnetometer has been designed and construction nearly completed. It is expected that this equipment will supplement or supplant, to some extent, the earth-inductor.

Three improved magnetograph-recorders, complete with special lamps and time-marking equipment, have been constructed. On these, as on all other magnetographs of the Bureau, gold ribbon has replaced the phosphor-bronze ribbon.

Two additional transits have been equipped with deflector-bars and magnets for the determination of horizontal intensity; they have been tested and standardized and are now ready for use in the field.

Special equipment has been devised for (a) magnetizing magnets to specific moments quickly and with sufficient accuracy, and (b) the measurement of temperature-coefficients of variometers at the observatories.

A new type of quartz-fiber suspension has been developed for H- and D-variometers; it is a modification of the la Cour type.

Improved magnetic observing-tents have been made of paraffined balloon cloth, and fitted

with special collapsible spreaders. These new tents are especially convenient for parties traveling by air.

Observatories

The five magnetic observatories of the Bureau continued in operation without interruption.

Cheltenham, Maryland--Routine and special standardization work has been conducted at the international standard observatory at Cheltenham, Maryland. Much of this standardization work has been made possible by the cooperation of the National Bureau of Standards which has standardized ammeters, resistances, and standard-cells as occasion required, especially for CIW sine-galvanometer 1, which continued to be used as standard in H. The Department of Terrestrial Magnetism of the Carnegie Institution of Washington has also continued its cooperation in maintaining the International Magnetic Standards.

Special observations were made to determine induction-coefficients and temperature-coefficients of magnets used in variometers and magnetometers.

Numerous types of compasses have been tested and reports prepared regarding them.

Honolulu, Territory of Hawaii--Electric light and power were installed at the Observatory during the year and extensive renovations were made in the quarters of the observers.

San Juan, Puerto Rico--A Cooke magnetometer equipped with cobalt-steel magnets and other improved accessories has been placed in operation; Alnico II magnets were later substituted for the cobalt-steel recording- and compensation-magnets.

Sitka, Alaska--An insensitive magnetograph was placed in operation. As at San Juan, Alnico II magnets were later substituted for the cobalt-steel magnets in this instrument.

Tucson, Arizona--Since the modified la Cour magnetograph, installed in the new variation-building, is performing satisfactorily, observations have been discontinued in the old variation-building and the building has been removed. The well has been deepened; this was made necessary by the recent lowering of the ground-water level.

The registration of earth-currents was discontinued at the Observatory in March 1943. This project had been carried on for the past several years in cooperation with the Department of Terrestrial Magnetism of the Carnegie Institution of Washington and American Telephone and Telegraph Company. Plans are under discussion for a resumption of this work.

Alnico II magnets have been substituted here also for all cobalt-steel recording- and compensating-magnets.

U. S. Coast and Geodetic Survey,
Washington, D. C.

RESEARCHES IN TERRESTRIAL MAGNETISM AND ELECTRICITY AT DEPARTMENT OF TERRESTRIAL MAGNETISM, CARNEGIE INSTITUTION OF WASHINGTON, FOR THE YEAR APRIL 1942 TO MARCH 1943

J. A. Fleming

During the year ending with March 1943, the normal program of investigations pursued by the Department has been subject to delays and curtailment due to the exigencies arising from the war. The widespread demands for application to the war-effort of the results of past and present investigations have emphasized the practical value of many aspects of the Department's researches in Earth-physics. Practically all facilities of personnel, laboratory, shop, and buildings at Washington and at the Observatories were devoted to investigations and solutions of war-problems. Members of the staff were assigned, upon request, to special duties elsewhere. Thus there has been possible only a limited continuation of the usual program; nevertheless, the work in all the sections has progressed, although on a reduced scale, and a considerable amount of worth-while research has been accomplished. Many items of scientific value were developed in the investigation of special war-problems.

Geomagnetic investigations

The investigations of methods of field-analyses and use of computing machines to facilitate such analyses were continued. To conclude the project of field-analyses by integrals on the theoretical side, an attempt was made to obtain a more compact expression for a function giving external current-systems corresponding to any observed magnetic field at the Earth's surface. Two methods previously developed gave a complete and exact solution but are rather slow in application. This function is intimately associated with the height of the electric current-system above the Earth compatible with observed surface-fields.

A study was made of the world-wide distribution of magnetic anomalies. Large anomalies appear in volcanic regions, where rocks such as granite and basalt, magnetized on cooling below the Curie-point, are likely to be common, and consequently in earthquake-zones. A collection was also made of material showing locations of ferromagnetic mineral deposits, where magnetic anomalies may be experienced.

The construction of new world isoporic charts for the epoch 1930-35 was continued and similar charts for the epoch 1940-45 were begun. Geomagnetic charts of the present epoch show large systematic errors, and the new isoporic charts should assist materially in providing the more accurate rates of secular change needed for their improvement and the best use of the available material. The isoporic charts developed at the Department by Fisk were tested for mutual consistency in the case of the isopors for horizontal intensity and declination. For declination, this method is being used in obtaining a compromise between the results of Fisk and Duvall for the region of the Pacific Ocean. The estimates based on Chapman's modification of Schuster's curl-method show marked evidence of inconsistencies, and the problem of adjustment of the isopors, so that the results for horizontal intensity and declination will be mutually consistent, is being studied.

Tables to correct field-observations for post-perturbation and annual variation were prepared for all days of the period 1905-37. Since disturbances vary both in number and in intensity with time of year, they contribute the major part of an apparent annual variation which, throughout low and middle latitudes is most marked in the geomagnetic north component, for which it has an amplitude of the order of about ten gammas.

The development of methods for the reduction of field-observations to mean of day on a world-wide scale was continued. For this purpose the solar daily variation (S_q), disturbance daily variation (S_D), storm-time variation (D_{st}), and irregular disturbances (D_L) were derived for individual days. Using estimates based on graphs for two or three stations, spaced roughly 120° and 180° apart in longitude in equatorial regions, the means according to hour of Greenwich time appear to give a rather good estimate of the storm-time variation.

Chapman continued his notes on isomagnetic charts. His Note VII deals with isoporic charts and their singular points. The nature of the isoporic lines was examined for the magnetic potential, V, and for the magnetic elements D, H, I, Z, and F. In the region around an associated pair of local dip-poles the isopors must be very complicated, those for D, for example, having at least eight singular points in the region. For isopors near the principal geomagnetic dip-poles, certain isoporic charts appear to be inconsistent with the theory. Discussion of the isoporic charts of the British Admiralty and of H. W. Fisk for 1922 for D and H showed, for 126 points uniformly spaced at 20° intervals, an average numerical difference between the indications of the two charts for $\dot{D}$ (that is, time-derivative) and for $\dot{H}$ of 56 and 69 per cent, respectively, at these points.

The eighth and last paper of the series relates to the mutual consistency of the declination and horizontal-intensity charts. The rate of change of the vertical component of the earth-air electric current-density (i) is expressed in terms of the surface-gradients of the rates of change of the horizontal magnetic elements X and Y or D and H; the formulas permit the calculation of (di/dt) from the distribution of the isomagnetic and isoporic lines for these elements. If the directions and spacing of the isoporic lines are seriously uncertain, (di/dt) determined from the magnetic charts should have a value of the order of five milliamperes per km^2 per year; this is confirmed by calculations based on the Admiralty charts for 1922, the Fisk isoporic charts for the same epoch, and the Swedish magnetic survey of epochs 1929.5 and 1936.5. The actual value of (di/dt) is inferred, from atmospheric-electric observations, to be at most 10^{-4}, so that these much larger calculated values of (di/dt) indicate errors in the isoporic charts.

The voluminous Wilkes' collection of manuscripts in the Division of Manuscripts of the Library of Congress was examined for the purpose of extracting values of the declination-observations made during the United States Exploring Expedition of 1838-42. Some references to the

magnetic work were noted and a few values ascertained, but the tables containing the results of the numerous determinations of the declination, which are known to have been obtained, were not found.

Many difficulties would beset the author bold enough to undertake the writing of a detailed and comprehensive history of geomagnetism because the early progress of that science is almost hopelessly enshrouded in the myths and legends of antiquity. There are, however, several documents which mark advances in the slow development of early geomagnetic knowledge and whose importance, from the historical viewpoint, is incontestable. Unfortunately, these documents are rare and access to them is extremely difficult because of their wide distribution in libraries and collections throughout the world. To mitigate this difficulty to some extent, G. Hellmann in 1898 reproduced some of the more important of these contributions in his "Rara Magnetica." This was a great service but the texts are in various languages of the thirteenth to sixteenth centuries, leaving them unintelligible to the majority of geophysicists. In order to remedy this condition and make this historical material generally available, the Department has undertaken their translation and publication. The first of these is the famous letter of Petrus Peregrinus de Maricourt on the magnet, "the oldest occidental treatise on magnetism." Several other translations and their introductions are in preparation.

Geoelectric investigations

An investigation was made of the relative effects of the wind on the two signs of conductivity. It was found that, on non-smoky days, the conductivities do not increase, but rather diminish somewhat with an increase in wind-velocity. On smokeless days, the air-earth current shows a slow increase with an increase in wind-velocity, particularly for the lower velocities. The conductivity shows a slow decrease with an increase in wind-velocity, becoming more or less constant for higher velocities than about five miles per hour. These results suggest that the smoke from more distant bush-fires has been dissipated horizontally by the wind, thus causing the total amount in a vertical column to be diminished as the wind increases in velocity. For still higher velocities, as much smoke is apparently brought into the region as is removed, thus accounting for the constancy of the conductivity and the air-earth current for higher wind-velocities. The ratio of positive to negative conductivity was found to diminish with increasing wind-velocity, as would be expected on the basis of a stratification of negative ions due to the Earth's electric field. The rate in the case of smoky days also decreases with increase in wind-velocity. The absolute value of the ratio for smoky days is much greater than for non-smoky days, consistent with a greater intensity of electric field on such occasions. The conductivities for smoky days are constant for a decrease in wind-velocity below about five miles per hour but increase with wind-velocities above this point. This is consonant with the idea that, for wind-velocities above five miles per hour, turbulence is sufficient to dilute the lower layer with air from higher layers having greater conductivities.

Intense smoke at the Watheroo Magnetic Observatory effectively increases the total resistance of the vertical column of air over the station. This, with other evidence, indicates that the smoke extends to a height of about one km. The total resistance of the vertical column of air over the Observatory varies greatly through the day. Both the variation and the average value are increased by the presence of smoke. Factors other than the number of condensation-nuclei and radioactive matter in the atmosphere, it is believed, may be effective in producing a diurnal variation in this total resistance. The intensity of smoke at Watheroo appears to be independent of the direction and velocity of the wind. The rate of ionization (small-ion production) in the lower atmosphere over a station on land is found to vary considerably through the day, being greatest during the early hours of the morning and least during the evening; the cause appears to be a variation in the amount of radioactive matter in the air.

Certain investigators have found that, during heavy thunder-storms, the number of small ions in the air may undergo an abnormal increase which has been attributed to the "Lenard effect" (production of charged particles through the breaking up of drops through splashing). Our records indicate that the number of small ions is not so greatly affected as is that of intermediate ions. The number of positive intermediate ions at such times may undergo a considerable increase which, however, cannot be attributed to the "Lenard effect," since the ionization (production of ions inside the closed thin-walled ionization-chamber) shows a similar change. Such a change in ionization must be accounted for by the action of radioactive matter, since the breaking up of water-drops would have no effect inside the closed chamber.

For the first time, strictly simultaneous atmospheric-electric data on sea and land have been compared. Such comparisons make it possible, on the basis of reasonable assumptions, to compute the total resistance of the vertical air-column of unit cross-section at the station on land. A total

of 42 complete fair-weather days during November and December, 1928, and January and February, 1929, from the Pacific Ocean and from the Watheroo Magnetic Observatory were utilized. The data were formed into two groups, (1) smoky days (when smoke was in the air at Watheroo) and (2) non-smoky days. The computed resistance of the vertical air-column at Watheroo has a pronounced diurnal variation with a minimum shortly before noon for both types of days. This is accounted for on the basis of two stratified horizontal layers of air, assuming that the resistivity of the upper layer is constant through the day, and that the lower layer is given by the conductivity-measurements near the ground. Half of the total resistance lies in the upper and half in the lower layer. The resistance of the lower layer varies with the resistivity; hence, the effective height to which the layer extends is constant at about 1.5 km.

Comparison of data from Huancayo Magnetic Observatory with those from the Pacific Ocean taken during October, 1929, indicates that the total resistance at Huancayo is independent of variation in resistivity of the lower layer, thus evidencing a very small thickness for the lower layer. The computed resistance for Huancayo is over three times that expected from consideration of the altitude of the station (3.3 km). This and other observed facts in atmospheric electricity at Huancayo are explainable on the assumption that a permanent bank of condensation-nuclei exists in the air a short distance above the ground there.

During the winter at Watheroo the potential-gradient varies through the day in a manner quite dissimilar to that found over sea. At times when the wind remains high, both night and day, the dissimilarity disappears. It thus appears that the cause of the dissimilarity is a pronounced diurnal variation in the conductivity of the lower air brought about by accumulated radioactive matte in the air adjacent to the ground during times when the wind-velocity is low and its subsequent dissipation after the increase in velocity. During the summer, condensation-nuclei also accumulate in the lower atmosphere and this tends to neutralize the effect of the radioactive matte.. Consequently during the summers at Watheroo the potential-gradient diurnal-variation curve closely resembles that found over the ocean.

An investigation of the electrode-effect in the atmosphere was made. It was found that theory and observation are in agreement, provided that the simple assumptions on which the theory is based are fulfilled. This made possible the utilization of the theory for obtaining approximate values for the combination-coefficients pertaining to small and large ions. Preliminary studies do not indicate large differences at three widely separated observatories (Huancayo, Watheroo, and Tucson). The value found for the coefficient is about 5.4×10^{-6} cc/sec.

Three ionization-chambers and an electrometer-assembly for use with them, designed primarily for the comparative determination of the radioactivity of rocks, were constructed in the Instrument-Shop of the Department. Preliminary tests have been made at the Department and more complete ones are under way by Professor V. Hess at Fordham University.

Nuclear physics

The depletion of staff and facilities by war-research activities again curtailed considerably the program in nuclear physics. Some progress was made in improved functioning of the pressure electrostatic generator, but reasonable expectations of four to five million electron-volts on the tube for this generator are not yet attained.

The 60-inch cyclotron installation was so well advanced, despite curtailment of personnel and difficulties in obtaining appurtenances, that satisfactory tests of magnet and vacuum-system could be made. The vacuum-pressure was less than 5×10^{-6} mm of mercury. The field of the magnet was found to be greater than 17,000 gauss, which promises an upper limit of probable deuteron-energy of about 27 million electron-volts.

The eighth Annual Conference on Theoretical Physics was held April 23-25, 1942, in Washington, D. C., under joint sponsorship of Carnegie Institution of Washington and George Washington University. The general subject was "The problems of stellar evolution and cosmology [see Science, v. 95, pp. 579-581, 1942].

Observatory-work

The Department's Huancayo (Peru) and Watheroo (Western Australia) Magnetic Observatories continued their regular geophysical program, including determinations of geomagnetic, geoelectric, ionospheric, and meteorological elements. The Magnetic and Ionospheric Observatory established last year at College, Alaska, in cooperation with the University of Alaska, particularly for investi-

gations of correlations of geomagnetic, ionospheric, and auroral work in polar regions, has continued in operation.

The cooperative program with the Cheltenham Magnetic Observatory of the United States Coast and Geodetic Survey was continued through the loan of CIW instruments for use in controlling standards in the horizontal and vertical components of geomagnetic intensity. Necessary observations for standardization and control of constants for CIW instruments were made before and after assignments to the field. The Department continued cooperation with the Apia Observatory in its geomagnetic program. Earth-current registrations, which had been made since March, 1931, under a cooperative arrangement between the American Telephone and Telegraph Company, Mountain States Telephone and Telegraph Company, the United States Coast and Geodetic Survey, and the Department, were discontinued March 1, 1943, when it was found necessary to resume commercial use of the lines. Records thus include approximately a sunspot-period and the data serve to give a fairly satisfactory description of the diurnal variation and its annual change.

Cooperation was also continued through loan of instruments with the Hermanus Magnetic Observatory, South Africa, the Royal Alfred Observatory, Mauritius, and the Apia Observatory, Samoa. Because of the war, cooperation was extended to the Godhavn Observatory by providing maintenance supplies and instrumental replacements making possible the continuation of the whole valuable program of this important station.

Survey-work

Because of limited available personnel and war-research activities, continuation of field-work to determine secular variation and new distribution-data has been chiefly effected through collaborative arrangements with other organizations. In Africa cooperation has been continued with the British East African Meteorological Service, in Australia with the Aerial, Geological, and Geophysical Survey of Northern Australia, and in New Zealand with the Magnetic Survey of New Zealand. In Central America, the West Indies, and the South American Republics, repeat-observations were made by the United States Coast and Geodetic Survey using CIW magnetometer-inductors 26 and 28--work generously undertaken by the Survey, in cooperation with the Latin-American Republics and the United States Department of State, as the Carnegie Institution of Washington was unable, at present, to make the 10-year series of reoccupations; the Institution was freely consulted in order that the high standards of the previous observations by its personnel should be maintained. Comparison-observations were made during these field-operations between the party's instruments and those of the Vassouras, Pilar, and Huancayo Magnetic Observatories.

Ionospheric investigations

Three complete automatic ionospheric recorders were in continuous operation at the Watheroo, Huancayo, and College Observatories. Interpretations of ionospheric reactions during magnetic storms were continued. Accumulated evidence indicates a post-perturbation effect, which may be world-wide in nature. Following several of the magnetic disturbances, simultaneous rapid decreases of the electron-density in the F_2-region were recorded both at Huancayo and Watheroo. The trend of recovery and the time of reaching normal conditions at both stations appear to be closely related.

The Department's policy of full cooperation with governmental agencies and with qualified representatives of allied governments was continued and extended.

The technique of measurement of intensity of the Earth's magnetic field in the ionosphere which was applied to observations at Huancayo may introduce an important new field of research linking ionospheric and geomagnetic analysis even more closely than at present.

Publications

The activities of the Department are set forth in greater detail in Year Book No. 41 of the Carnegie Institution of Washington.

The series of quarto volumes entitled "Scientific results of Cruise VII of the Carnegie during 1928-1929 under command of Captain J. P. Ault" was begun by the publication of three volumes of biological results (Biology I, II, and III) and two volumes of meteorological results (Meteorology I and II); Biology IV, consisting of a number of individual reports, is in the hands of the printer. It is expected that two volumes of reports and discussions of physical oceanographical results (Oceanography I and II) will appear later in 1943. Other volumes of the series will cover additional reports on biological, chemical, and physical results.

A few of the principal papers published during the last year are listed below.

Sydney Chapman, Notes on the lunar geomagnetic tide: I--Its mathematical and graphical representations and their significance, Terr. Mag., v. 47, pp. 279-294, 1942.
Sydney Chapman, Notes on isomagnetic charts: VI--Earth-air electric currents and the mutual consistency of the H and D isomagnetic charts, Terr. Mag., v. 47, pp. 1-13, 1942.
Sydney Chapman, Notes on isomagnetic charts: VII--Mathematical notes on isoporic charts and their singular points, Terr. Mag., v. 47, pp. 115-138, 1942.
Sydney Chapman, Notes on isomagnetic charts: VIII--The mutual consistency of the declination and horizontal-intensity isoporic charts, Terr. Mag., v. 47, pp. 139-146, 1942.
Sydney Chapman and A. M. Mian, The rate of ion-production at any height in the Earth's atmosphere: I--The spherical harmonic representation of its world-wide distribution; II--The Fourier expression for its daily variation, Terr. Mag., v. 47, pp. 31-44, 1942.
J. A. Fleming, Geomagnetism in Latin America, Proc. Eighth Amer. Sci. Cong., Washington, D. C., 1940, v. 7, pp. 47-56, 1942.
O. H. Gish, Further evidence of a latitude-effect in potential-gradient, Terr. Mag., v. 47, pp. 323-324, 1942.
H. D. Harradon, The variations of geomagnetism, Sky and Telescope, v. 1, pp. 12-17, 1942.
H. D. Harradon, Some early contributions to the history of geomagnetism I, Terr. Mag., v. 48, pp. 3-17, 1943.
M. W. Jones and P. G. Ledig, On the anomalous diurnal variation of air-conductivity and potential-gradient at the Huancayo Magnetic Observatory, Trans. Amer. Geophys. Union 1942, pt. II, pp. 301-304, 1942.
I. Lange and S. E. Forbush, Note on the effect on cosmic-ray intensity of the magnetic storm of March 1, 1942, Terr. Mag., v. 47, pp. 185-186, 1942.
I. Lange and S. E. Forbush, Further note on the effect on cosmic-ray intensity of the magnetic storm of March 1, 1942, Terr. Mag., v. 47, pp. 331-334, 1942.
W. E. Scott, The mutual consistency of successive monthly means of declination, Huancayo Magnetic Observatory, Terr. Mag., v. 48, pp. 45-48, 1943.
H. B. Silsbee and E. H. Vestine, Geomagnetic bays, their frequency and current systems, Terr. Mag., v. 47, pp. 195-208, 1942.
E. H. Vestine, The reduction of magnetic observations to epoch, Part I, Terr. Mag., v. 47, pp. 97-113, 1942.
G. R. Wait, Electrical resistance of a vertical column of air over Watheroo (Western Australia) and over Huancayo (Peru), Terr. Mag., v. 47, pp. 243-249, 1942.
G. R. Wait, Effect of smoke on the atmospheric-electric elements at the Watheroo Magnetic Observatory, Terr. Mag., v. 48, pp. 49-63, 1943.
H. W. Wells, Effects of solar activity on the ionosphere and radio communication, Proc. Radio Eng., v. 31, pp. 147-157, 1943.

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DISCUSSIONS OF RECENT METHODS OF REDUCING FIELD OBSERVATIONS TO EPOCHS

P. H. Williamson, E. H. Vestine, and H F. Johnston

This was an informal discussion of recently developed methods of reducing field-observations to epochs and no manuscripts were prepared for publication. A general formulation of the problems was presented and followed by discussions of the modes of attack being pursued and of the inherent difficulties involved in removing the effects of fluctuations resulting from disturbances and other more systematic variations.

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AMERICAN GEOPHYSICAL UNION

TWENTY-FOURTH ANNUAL MEETING

SECTION OF OCEANOGRAPHY

REPORTS AND PAPERS

Washington, D. C.
April 23, 1942

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THE OCEANOGRAPHIC WORK OF THE UNITED STATES HYDROGRAPHIC OFFICE DURING THE PAST YEAR

G. S. Bryan

For the second time since the United States entered the war, we are meeting to discuss our oceanographical activities. All of us realize that our work, while unspectacular, is having a vital influence on the nation's war effort. There is hardly an activity in the Navy that is not turning to the oceanographer for assistance in problems that have arisen in connection with the war. All oceanographic information that has been accumulated in the past is now being examined for its possible utilization in winning the war.

This is especially true in the Hydrographic Office, which has been the repository, since the days of Maury, of oceanographical data gathered from the seven seas by the United States Navy and mariners of all nations. Laboriously, voyage after voyage, the cooperating observers of this Office set down their observations of currents, sea-water temperatures, and other cognate phenomena. There were those who sometimes doubted that the collection of all this material by the Hydrographic Office had any practical value, but today this vast reservoir of information is paying big dividends. A steady flow of charts embodying the findings that have been disclosed by the evaluation of the data is now going to our fighting ships and to those of the United Nations to better enable them in fulfilling their missions.

While naturally I would like to discuss the results that have been achieved by the Office under the impetus of war, the disclosure of these details must wait until the final victory is achieved.

A constant demand is being made on the Hydrographic Office by the various governmental agencies and scientific institutions for all available oceanographic data. To help coordinate these requests, the Hydrographic Office has been fortunate in obtaining the services of Roger Revelle from Scripps Institution of Oceanography and Miss Mary Sears from Woods Hole Oceanographic Institution, both serving as commissioned officers of the Navy. This arrangement will do much to enhance the mutual cooperation that has existed between between the scientific institutions and the Navy.

Since our last meeting the Hydrographic Office has been transferred to a building of its own. From time immemorial the Office had been hampered by lack of space. The Hydrographer's Report for 1872 stated "the printing of this Office is carried on in cellar rooms, so damp and rotten that no private party would think of using them; and make-shift rooms have had to be fitted up in the loft of a stable, for draftsmen and stowage." While in recent times conditions had materially improved, the vast war expansion necessitated drastic measures to relieve a condition that was becoming chaotic. Funds were obtained and a three-story building containing over 160,000 square feet of floor space was erected at Suitland, Maryland. This building, designed especially for the Office, is equipped with the most modern machinery for chart-making. However, the unprecedented demand for charts is already taxing the facilities of the new building and plans have been approved for an additional wing of 25,000 square feet to be erected shortly. The personnel of the Office, which a few years ago was less than 200, is rapidly approaching the 1,000 mark.

While, as previously stated, I am unable to discuss many phases of the oceanographical work accomplished by this Office during the past year, I can with propriety tell you something that will be of interest to oceanographers and geographers alike relative to a new chart of Antarctica (H.O. Chart No. 2562) which has just been completed by this Office. This chart will be supplemented by "Sailing Directions for Antarctica" (H.O. Publication No. 138). Both the chart and the Antarctic Pilot were compiled by Commander R. A. J. English, U.S.N., who served as Commanding Officer of the Bear on the Byrd Second Antarctic Expedition, later as Executive Secretary of the United States Antarctic Service, and who was detailed to the Hydrographic Office to compile the results of this and previous expeditions for publication.

This chart, on the scale of 1:11,250,000, is printed in 12 colors, and represents the most comprehensive picture of the Antarctic regions yet produced. In it are embodied the results of all explorations to 1941. The sources are as follows:

Commencing at the Ross Sea and traveling in a counter-clockwise direction, we have Victoria Land from British surveys. Then Wilkes Land delineated from the original work of the American

explorer Wilkes. Details around King George V Land and the Adelie Coast came from British and French sources, respectively. The Banzare Coast was explored by the British-Australian-New Zealand Antarctic Research Expedition. It is interesting to note that the name Banzare was coined from the first letter in each word of the expedition that explored this territory. Data on Queen Mary Coast are from the early British exploration, while the information on Wilhelm II Coast comes from German Sources. Princess Elizabeth Land was mapped by recent Norwegian expeditions, as was part of Mac-Robertson Land. The remainder of Mac-Robertson Land and part of Enderby Land were covered by Norwegian and British surveys. The penetration into Princess Elizabeth Land was the result of a plane flight by Lincoln Ellsworth. The rest of Enderby Land and a portion of Queen Maud Land was compiled from the latest expeditions of Norwegian explorers. The extensive topographic development in the remainder of Queen Maud Land is from a recent German survey, which utilized air photography to a great extent. The south coast of Weddell Sea from Cape Norvegia to Dawson Lambton Glacier was taken from early British sources, while from here to and including the Filchner Ice Shelf the information comes from an early German expedition. The south coast of Weddell Sea is the largest unexplored area left on the coast of Antarctica. With the exception of the outer extremities, Palmer Peninsula, named for the famous American explorer who was the first man to sight the Antarctic Continent, and the remainder of coast of Antarctica from 60° west to 180° west is based on recent United States explorations. This area, which is one-third of the perimeter of the continent, has been compared to the Siberian Coast of the Arctic.

From the foregoing, while it can be said that the exploration of Antarctica has been truly international, the contributions of the United States are considerable. Outstanding among the accomplishments of the modern American explorers were: Ellsworth's longest flight from the tip of Palmer Peninsula to Little America; Byrd's flights and discoveries in the Ross Ice Shelf Area, and English's survey of the edge of the Ross Ice Shelf Area. These, combined with the mapping expeditions of Ellsworth, Byrd, and the United States Antarctic Service, form a record of which this nation can well be proud.

Turning now to the bathymetry of the chart, which is shown in various shades of blue, we find that the names assigned to the oceanic features were taken from two sources, the Antarctic Chart of the American Geographical Society prepared by Dr. Joerg and the Bathymetric Chart compiled by Professor Wüst, which were published in the Hydrographic Review, November 1936. Names for new features, such as the Howe-Chesterfield Swell, brought to light by the additional soundings incorporated in the new chart, have been assigned by the Hydrographic Office. Such names are tentative pending a decision by the International Association of Oceanography.

A brief description of the bathymetric features of the chart are as follows:

The wide gently rising elevation that traverses the whole of the Atlantic Ocean, the Mid-Atlantic Swell, terminates in the Antarctic waters at about 50° south This swell divides the South Atlantic into two parts. To the east is the Cape Basin and the Angola Basin which are separated from each other by Walvis Ridge. The southern limit of the Cape Basin is not clearly defined, but an examination of the soundings shows a slight rise although it is not outlined by fathom-curves. This rise has been named the Cape Rise by some oceanographers To the west of the Mid-Atlantic Swell are two basins known as the Brazilian and Argentine basins, respectively, separated by the Rio Grande Swell. Shown on most bathymetric charts as a "ridge", as outlined on this chart the term "swell" seems more applicable. The Brazilian Basin extends northward beyond the limits of this chart, while the Argentine Basin trends southward to the Scotia Arc.

At the termination of the Mid-Atlantic Swell, a definite rise of the bottom makes off to the eastward to longitude 25° east. Here across a deep saddle is the end of the Crozet Swell, an Indian Ocean feature protruding from the Crozet Islands. North of these elevations is the Agulhas Basin which is bounded on the north by the Cape Swell and the continental shelf of Africa.

The Atlantic-Indian-Antarctic Basin is the largest definite basin adjacent to the Antarctic Continent. It wraps itself around the continental shelf of Antarctica from Palmer Land on the west to the Kerguelen-Gaussberg Ridge on the east. To the north it is bounded by a part of the Scotia Arc, the Atlantic-Indian Swell, and the Crozet Swell. The deepest area of this basin, named by Sir John Murray as the Valdivia Deep, lies along the parallel 60° south from the meridians 30° to 50° east

The Scotia Arc, a chain of connected islands and banks, extends from Tierra del Fuego through Burtwood Bank, South Georgia, the Sandwich Group, the South Orkney Islands, the South Shetland Islands to the Palmer Peninsula. Inside the curve of this Arc is the Scotia Sea. The

western end of the Scotia Basin is a definite rise of the ocean floor extending from the Palmer Peninsula northward to Cape Horn, which might well be named Palmer Swell. At the northeast curve of the Scotia Arc, adjacent to the South Sandwich Islands, is the South Sandwich Trench, containing the Meteor Deep. This trench is separated from the Argentine Basin by the South Sandwich Swell.

The Crozet Swell on which is located the Crozet and Prince Edward Islands extends in an east-west direction. The name "swell" has been used as the word "ridge" does not seem appropriate for such a gently sloping elevation. Between this swell and the African coast a section of the Madagascar Basin is shown on the chart. There is deep water between the Crozet Swell and the Kerguelen-Gaussberg Ridge. The latter is continuous with the Mid-Indian Swell, which does not appear on the chart, and is a narrow steep-sided formation extending from the Kerguelen Islands towards the mainland of Antarctica in the vicinity of Mount Gauss.

Farther eastward in the Indian Ocean there is a slight elevation from the Mid-Indian Swell to the Macquarie Swell. This feature is in the nature of a swell and has heretofore been considered as a part of the Mid-Indian Swell. The Hydrographic Office has tentatively assigned the name Indian Antarctic Swell to this feature, which separates the Indian Antarctic Basin from the South Australian Basin. The latter lies due south of Australia and extends from Tasmania on the east to beyond the limits of the chart on the west. In this basin will be found the Jeffery Deep of Murray.

Adjacent to the Antarctic continental shelf south of the Indian Antarctic Swell is the Indian Antarctic Basin extending from the Macquarie Swell in the east to the Kerguelen-Gaussberg Ridge in the west.

The Macquarie Swell is a chain of islands and banks, more or less connected, which stretch from Tasmania through Mill Bank, Macquarie Island, Hjort Seamount, Balleny Islands to Victoria Land on the Antarctic Continent. This swell divides the Indian from the Pacific oceanic features.

Although designated as Macquarie Swell on the chart, this formation is not strictly speaking a swell consisting as it does of a continuous series of shoalings separated by deep water. A more descriptive term would be "Searange"

Lying between the Macquarie Swell on the south, the New Zealand Plateau on the east and north, and the Australian continental shelf on the west is the East Australian Basin, which forms the floor of the Tasman Sea. The Thomson Deep is a narrow, steep-sided trough in this basin lying along the continental shelf of Australia.

The Pacific Ocean portion is divided into two parts by the Easter Island Swell which cuts across that ocean from the Macquarie Swell diagonally to Easter Island. To the south of this swell lies the Pacific Antarctic Basin. This basin is bounded on the east by the Palmer Swell and the continent of South America and on the south by the Antarctic continental shelf.

North and west of Easter Island Swell is the South Pacific Basin which extends west to the Macquarie Swell, the New Zealand Plateau, and the Kermadeck Ridge. The most important feature of the portion of that basin shown on this chart is the Kermadeck Trench within which is located the Aldrich Deep.

It should be noted that Byrd Deep has not been incorporated on the chart. Although reported in latitude 61° south, longitude 179° east, with a depth of 4692 fathoms, the navigational data upon which its position was fixed were not deemed accurate enough to warrant its inclusion. It is hoped that a future expedition will definitely determine its position.

In conclusion, I wish to state that all the resources of the Hydrographic Office, through the Coordinator of Research and Development, have been placed at the disposal of scientists who are aiding this Government in the mighty struggle for the preservation of civilization. With the return of peace, when the activities of the oceanographers who are associated with this Office and other services of the Government can be discussed, I am sure that many facts will be revealed showing that during the war period the Hydrographic Office contributed in no small manner to the advancement of oceanography and the ultimate victory, through surveys, investigations, and publications covering veritably the globe from "Greenland's icy mountains to India's coral strand."

U. S. Hydrographic Office,
Washington, D. C.

BRIEF CONDENSED RESUMÉ OF ACTIVITIES OF THE COAST GUARD DURING 1942

R. R. Waesche

In the pre-war years the Coast Guard has been privileged to contribute information and data on its oceanographic activities for the proceedings of the annual meeting of the American Geophysical Union. The prosecution of the war has necessarily ended this customary practice which related primarily to the scientific work associated with the International Service of Ice Observation and Ice Patrol in the North Atlantic which was suspended until further orders by Executive Order of December 20, 1941.

During 1942 all the efforts of the Coast Guard were directed towards winning the war. Since the Service had been transferred from the Treasury Department to the Navy on November 1, 1941, upon the declaration of war on December 8, 1941, it was already operating in its prescribed role as a part of the Navy. The larger cutters and patrol boats, capable of offshore operations, served with the Fleet, Naval Sea Frontier, and Task Forces for convoy, anti-submarine, and patrol duty. The Greenland Patrol was made up largely of Coast Guard units, by reason of the experience of the Service in Alaskan and other American waters where heavy ice-conditions are encountered. Buoy tenders were engaged in the establishment of mine fields and other anti-submarine defenses; the chain of lifeboat and light stations, and lookout stations, along the coast, supplemented by beach patrols, were strengthened to insure the whole coastal expanse of water being kept under vigilant surveillance. The landing of four enemy saboteurs on the Long Island coast in June, 1942, was immediately detected by the beach patrol, leading subsequently to the capture of eight enemy agents who had so landed on the Long Island and Florida coasts. In addition to patrols by foot and automotive means, mounted horse patrols and patrolmen accompanied by especially trained dogs were added to the force.

In cooperation with the Naval Sea Frontier Forces in coastal anti-submarine measures, every available cutter and patrol boat especially adapted to the coastal convoy system, and every available motorboat, yacht, fishing vessel, and other small craft that could be converted to naval use, were pressed into service and manned by the Coast Guard, establishing a continual coastal picket and patrol line. The manning by the Coast Guard of this inshore patrol, coastal convey, and coastal picket forces, operating in close cooperation with airplane patrols, was an important factor in the great reduction in the sinking of merchant vessels by enemy submarines, and also instrumental in reducing loss of life by reason of their presence for rescue-operations.

Coast Guard personnel were utilized in manning naval transports and in landing-boat operations of the naval amphibious forces in Guadalcanal, the Southwest Pacific, and North Africa.

Through its captain of the port organization, the Coast Guard enforced regulations issued pursuant to the Espionage Act of 1917, governing the anchorage and movements of vessels, the searching of vessels and persons thereon, the boarding and guarding of vessels in our harbors, and the supervision of the handling of explosives and other dangerous cargoes aboard vessels. Also the responsibility of the Secretary of the Navy for the protection of merchant shipping, ports, and waterfront-facilities from damage through accident or sabotage was delegated to the Commandant of the Coast Guard. To insure the safe and prompt movement of merchant vessels, and of the massive stores of war material at our ports, measures were taken for surveillance over all pertinent activities involving the safety, the investigation of persons, and issuance of millions of identification cards; organization of the world's largest fireboat force; establishment of fire-prevention training; creation of volunteer security forces, and placing plant guards at strategic war plants under military control and discipline.

Activities of the former Bureau of Marine Inspection and Navigation were consolidated with the Coast Guard in the interest of expediting the prosecution of the war and integrating and consolidating maritime safety and protective measures in one agency. Every possible measure has been taken to add to the safety of the men manning our merchant marine and of the cargoes moving aboard the vessels.

The system of aids to navigation--lighthouses, buoys, radio-beacons, etc.--were adapted to wartime conditions and to meet military requirements. Ice-breaking operations were carried on to insure the maximum utilization of our navigable waterways in the transportation of iron ore, fuel, and other essential commodities in the prosecution of the war. Control was assumed over pilots and pilotage to insure the safe, prompt, and orderly movement of vessels and a reduction of pilotage fees in certain cases.

In its combatant operations which extend to practically all scenes of engagement with the enemy upon the sea and coast, officers and men of the Coast Guard have made the supreme sacrifice. The enemy has been dealt blows of avengement, and the growing list of officers and men who have distinguished themselves in line of duty is testimony that the Service is exacting its toll in combatant service and giving added honor to the proud record of the Service throughout the war history of our country.

U. S. Coast Guard,
Washington, D. C.

OCEANOGRAPHIC ACTIVITIES OF THE UNITED STATES COAST AND GEODETIC SURVEY

L. O. Colbert

The oceanographic activities of the United States Coast and Geodetic Survey are being further curtailed because of war conditions. All offshore operations have been stopped and hydrographic surveys are being limited to areas near the coast or along shore and in harbors and intercoastal waters. These surveys, however, are important to the national defense and are being made at the request of the armed forces. In view of the confidential nature of the work, no reference will be made to the localities.

During the past two years, two large survey-units have been added to our fleet--the Explorer and the Pathfinder--and five small ones. On the other hand, six large units have been transferred to the Navy for the duration.

Development work has continued on our new radio current-meter. The motor vessel E. Lester Jones this winter is carrying on a current-survey in Puget Sound, using five of these meters with their streamlined buoys. Six additional meters will be delivered from the manufacturer in the near future. Plans are being made for the shipment of the meters and buoy-equipment to the Atlantic Coast later this spring for making two current-surveys on this coast requested by the Navy.

Radio current-meters have the advantage over old methods in that one vessel can make observations at several current-stations at the same time by tuning in on the radio current-buoys at frequent intervals, whereas in the past the vessel could occupy only a single station. Another advantage is that the streamlined current-buoys can be held on station during bad weather and in the strong currents with less difficulty than a ship can be anchored under such conditions.

In addition to the Puget Sound current-survey already mentioned, a number of special current-surveys have been conducted to furnish data requested by the armed forces and by organizations engaged in shipbuilding and similar war activities.

In the field of tides, observations were continued with special emphasis on their application to the war effort. Normal expansion of our system of primary tide-stations has been retarded by the war and new activities have been limited to projects originating with specific needs of the armed forces.

A special tide-survey of the Columbia River in cooperation with the United States Engineer Office at Portland, Oregon, was completed. This is the latest of a series of such surveys which were begun in 1933 and include the outer coasts of Oregon and Washington, Strait of Juan de Fuca, Puget Sound, San Francisco Bay, Sacramento-San Joaquin Delta, and Los Angeles-Long Beach Harbor. The latter survey was primarily concerned with investigation of the complicated seiche movements in that waterway. Similar tide-surveys for a number of important waterways on the Atlantic coast are needed and were in the planning stage when the war forced their curtailment.

The program of cooperative tide-observations in Central and South America was continued during the year at 14 stations stretching from Mexico to the Strait of Magellan. These are furnishing not only detailed facts with regard to the local tides, but also the needed data for determining changes in relative elevations of land and sea. As a result, too, of these observations the tide tables will contain daily predictions for these ports.

During the year some interesting seiche movements, arising from seismic disturbances, were recorded on several of these gages.

U. S. Coast and Geodetic Survey,
Washington, D. C.

NEW EVIDENCE REGARDING DEEP-WATER FLOW IN THE EASTERN PACIFIC

Eliot G. Mears

In gathering data concerning the Humboldt Current, the present investigator has discovered evidence not previously utilized, which indicates that Antarctic circumpolar water flows along the eastern shores of the Pacific as far north as the latitude of southern California, in what appears to be an uninterrupted movement from Antarctic regions. The first proof and statement of this direction of deep-current flow we owe to Austin H. Clark, based upon his study of crinoid distribution.

According to Clark, the sole possibility is for crinoids "to pass from water of one origin into that of another, provided there are no marked differences in temperature, oxygen content, or salinity between the two waters." But since water of these properties would normally have the same origin as other water of similar character, and since attached forms are spread chiefly by currents, hence, "the distribution of bottom animals gives an indication of the course of bottom currents", or of currents along shore within the depths occupied by animals of fixed growth.

Because of this fact, Clark, in 1914, pointed out that crinoid distribution showed a movement of abyssal water from the vicinity of Cape Horn along the western edge of the two Americas to the Gulf of Alaska, thence to the extreme western limit of the Aleutian Islands, and then, after an unexplained break, down the eastern and southern sides of the Japanese Islands proper. Detailed data have not yet become available for the entire stretch of crinoid extension, but northward from Cape Horn to southern California, actual findings of recent marine research corroborate the foregoing indication of deep-water movement in the extreme eastern Pacific.

In the main, oceanographers agree that Pacific deep water originates outside the Pacific itself, mostly in the Mediterranean and Red seas (Sverdrup, 1942, p. 157). Therefore, Pacific deep water, entering from south of Australia, and having been much longer removed from contact with the air than that of the other two oceans, is poorer in oxygen content, and becomes progressively more so in the course of its flow within the Pacific. The eastern and northern Pacific deep water has less oxygen than the southern and western.

For this reason, some investigators have concluded that there is a slow movement of Pacific deep water across the equator on the western side of the ocean to the north and southward down the eastern rim of the ocean, for there is no outlet sufficiently deep in the north through which Pacific deep water might flow. But since the oxygen content is the one bit of evidence upon which this supposed movement is based, the dive which the cold surface current, the Oya Shio, makes off the coast of Hokkaido along the eastern shores of Japan (Ito, 1930), might easily furnish the additional oxygen found in deep water in the western part of the Pacific, particularly since the cold stream appears to be lost by mixing before it reaches Formosa.

Besides, the other evidence points directly to the northward movement of circumpolar deep water in the far eastern Pacific. Deacon found deep water with a southward trend everywhere in the circumpolar cruise of Discovery II, except over Easter Island Ridge, and north and directly east of Peter the First Island in Bellingshausen Sea, notably the latter. Deacon specifically states that "between 80° and 90° west the deep water in 55° south has the properties similar to those which are only found in 65° south across the greater part of the ocean farther west. The northward movement appears to bring about a large reduction in the volume of the deep water flowing towards the east." And he is quite certain that the Scotia Arc, formed by the islands and submarine ridge between Cape Horn and Graham Land, marks the "terminal" region between the Atlantic and Pacific deep currents." In other words, deep water does not escape from the Pacific into the Atlantic in the eastern part of the Pacific in any appreciable amounts; actually, most of it turns northward in this vicinity.

Regarding the bottom water, Deacon observes that "a more careful examination of the data must be made before it is possible to say what happens to the final traces of water from the circumpolar bottom water; part of the current may continue towards the east through Drake Passage above the colder water which flows westward from Scotia Arc, but it is also possible that the whole of the current bends towards the north in the eastern part of the Pacific Ocean together with the highly saline deep current." He is definite in the contention that "the distribution of salinity, temperature, and oxygen content in the most saline stratum of the deep layer in the southeastern part of the ocean . . . indicates that the highly saline current from the Indian and Atlantic oceans is turned towards the north as it approaches the western end of the Drake Passage." (1937, pp. 104, 116.)

Sverdrup, who believes that the deep current must pass over Scotia Arc and thus escape from the Pacific into the Atlantic, admits that "within the Antarctic Ocean" west of Drake Passage is the only region "in which there is evidence of a marked discrepancy between the lines of equal transport and the actual flow of water," for "the line stops against the continent to the west of Drake Passage." He interprets this interruption to mean "that in Drake Passage and the Scotia Sea the water does not flow parallel to the dynamic contour lines but flows uphill." (1942, pp. 206-207.) It would appear, however, that it is more satisfactory to follow Deacon and Wüst (1929) in the acceptance of the presence of northward flow in the deep current immediately west of Drake Passage.

Sverdrup's contention that the deep current in the southeastern Pacific is flowing southward, that is, when the motion can be determined at all, is at variance with his earlier observations. In his report to the American Geophysical Union in 1930, he stated that the Carnegie found, in the locality "from about 98° west longitude and 40° south latitude to Callao," that the Antarctic Intermediate Current mixed with the current above it but not with the deep current below it (1930, p. 262). Gunther (1936) has shown that the current above the Antarctic Intermediate Current is the southward moving Return Current. It is known that the Antarctic Intermediate Current in the eastern Pacific moves northward. If the deep current directly beneath it does not mix with the intermediate current, it seems as though both currents were moving in the same direction, that is, northward.

Relative to deep water, Sverdrup, Johnson, and Fleming find that conditions in the Indian Ocean "appear to be more or less similar to those in the South Pacific" (1942, p. 755), a result which would naturally follow the closer connection between the Indian Ocean and the South Pacific than between the Indian Ocean and the North Pacific. These authors state also that, in the equatorial Pacific at depths from 50, 100, to 200 meters below the surface, there is "an Equatorial Water Mass of a remarkably uniform character which extends over the entire Pacific from east to west. . . . This Equatorial Water Mass has its greatest north-south extension along the American coast, where it is present between latitudes 18° south and 20° north." This body of water is so uniform that they make no effort to subdivide it below the discontinuity surface layers. (1942, p. 706.)

Sverdrup, when reviewing the findings of the Carnegie, remarked that the deep water of the South Pacific "is of such a uniform character that no definite conclusions as to the movement of this water can be drawn from the available data." (1933, p. 145.) The observations of the Carnegie extended from the higher latitude of 40° south to Callao at 12° south. In the previous quotation from Sverdrup and his associates is the statement that the Equatorial uniform mass of water extends near the American shores in the eastern Pacific to 18° south latitude. Here is an overlapping of 6° of latitude, in which, evidently, the deep water of the South Pacific, which started northward between 80° and 90° west longitude, is said to be identical with that uniform Equatorial Water Mass which extends across the entire width of the Pacific in equatorial regions; but this mass extends farther north in the far eastern Pacific than elsewhere.

This very extreme northward extension of deep South Pacific water in the far east of the Pacific is another evidence that the current flows north in that vicinity and, therefore, possesses its greatest volume there. Similarly, the fact that the Equatorial Water Mass attains its nearest approach to the surface, namely, within 50 meters, in the east, while it descends to 150 and 200 meters toward the west (Sverdrup, Johnson, Fleming, 1942, p. 708), is further indication that the mass of water originates or flows from the south to the north along the eastern rather than the Western Pacific sector.

Below surface layers, there appears to be no break in the deep-water extension northward until it is off the south coast of Lower California in about 23° north latitude, where the Scripps' scientists find that, "Subarctic Water converges with Equatorial Water"; yet even at 25° 22' north, there is equatorial-type water that can be distinguished below depths of 300 meters. Indeed, in the eastern Pacific, "below 300 meters the stations between latitude 22° north and 45° north show T.-S. (temperature-salinity) curves intermediate in character of the true Subarctic Water and the true North Pacific and Equatorial Water; this fact suggests that the water at these stations is formed by lateral mixing between these two large and well-defined water masses. Such mixing is facilitated by a northward penetration along the coast of water that contains a large component of Equatorial Water" (1942, pp. 713, 714).

This meeting of Subarctic Water mass off the coast of Lower California explains, perhaps, the deepening of the range of species of crinoid which Clark, in 1914, found to be identical in the Magellanes, in the Gulf of Panama, and off the coast of southern California. The range of the crinoid genus Florometra was 295 meters in the Magellanic areas, 893 meters in the Bay of Panama, but 1825 meters, or from depths of 36 meters to 1942 meters (more than a mile deep),

off the coast of southern California. Off the southern California station occurred the greatest depth range of the genus; northward, it was greatly curtailed, even as the above investigators found to be true of Equatorial Water (or what appears to be South Pacific and circumpolar, northward moving deep water). Off southern California the upper extension of Florometra was 48 meters, or 2 meters less than the above oceanographers discovered to be the average surfaceward extension of the uniform Equatorial Water Mass in portions of the equatorial regions (pp. 707-708).

It is interesting, also, to record that the Albatross (Murray and Lee, 1909) found the northern extreme of the notable manganese-iron sediments, with their unusual development in bottom deposits of the Humboldt Current area, were located somewhat southward from that offshore California station, cited by Clark, which provided the greatest vertical range of Florometra. The present investigator conjectures that the manganese-iron accentuation in the South Pacific may be traced to the manganese and iron shorewise deposits of Chile and Peru in the vicinity of the vast American trenches off the west coast of South America. Should further investigation confirm this hypothesis, the concentration of manganese-iron nodules near Florometra's widest vertical range, in the general locality where the Subarctic and Equatorial Water masses meet, there would be another confirmation of crinoid evidence.

Our fresh use of accepted facts regarding currents in the eastern Pacific awaits not only new data, but also more careful scrutiny of present and potential research from various fields allied to physical oceanography, of which Clark's significant finding nearly three decades ago is a striking illustration.

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RESEARCH WITHIN PHYSICAL OCEANOGRAPHY AND SUBMARINE GEOLOGY AT THE SCRIPPS INSTITUTION OF OCEANOGRAPHY DURING APRIL 1942 TO APRIL 1943

H. U. Sverdrup and Staff

(Contribution from the Scripps Institution of Oceanography, New Series, No. 207)

Academic research activity in the fields of physical and chemical oceanography and submarine geology has been further curtailed during the past year due to increased participation of mem-

bers of the staff in war work. Several members are on special war leave and, since August, 1942, the remaining personnel in physical oceanography and the facilities of the Scripps Institution have been completely at the disposal of special war projects. Consequently, there is little to report to the American Geophysical Union.

G. F. McEwen has temporarily discontinued various research activities in progress with the view of resuming his work when conditions make this possible. The climatology-investigations with Gorczynsky were concluded with the exception of a statistical paper by McEwen, completed later. The usual work on long-range weather forecasting was definitely terminated, and the material placed in storage. It is the belief that the Government investigations in this field, brought about by increased demands, will lead to a use and expansion of Government facilities and personnel in this field somewhat comparable to the complexity and importance of the problem. Work on the problems of dispersion and turbulence was stopped, and the material indexed and filed. The material on computing surface-currents from sea-surface temperatures was indexed and filed, with the intention of continuing these researches, to a limited extent, along with the war work.

The usual observations of temperature, salinity, and weather at our six shore stations and supplementary observations from United States Lighthouse Tenders have continued. There were about 2200 salinity observations, 2200 sea-temperature observations, and 1500 wind observations. Continuous barograph and pyrheliometer records and daily observations of humidity and precipitation were maintained at the Scripps Institution.

Under the direction of E. G. Moberg, J. C. Hindman has nearly brought to a conclusion the investigation begun last year on equilibria in the system calcium carbonate-carbon dioxide-water in salt solutions and sea-water. This work was undertaken with a view of gaining further information regarding the much-investigated problem of the solubility of calcium carbonate in sea-water at various temperatures, salinities, carbon-dioxide tensions, and, indirectly, hydrostatic pressures. The essential procedure consisted of equilibrating, at various temperatures, natural sea-water samples in a thermostat with solid calcium carbonate, the equilibrium being approached both from undersaturation and supersaturation with respect to calcium carbonate. When equilibrium had been established the carbonate ion-content was determined by electrometric titration with a standard acid, using the most advanced types of glass electrodes, a high-grade potentiometer, and a sensitive electron-tube voltmeter previously developed and described by L. J. Anderson and J. C. Hindman (Ind. and Eng. Chem., v. 15, pp. 42-45, 1943). With this apparatus assembly, hydrogen-ion concentration values accurate to pH 0.01 or better were obtained. In a number of experiments various types of salt solutions were substituted for natural sea-water in order to ascertain the possible effect on the calcium equilibrium of the minor substances, especially organic matter, contained in sea-water. The data obtained from this study are now being analyzed and no final conclusions can as yet be drawn. It can be stated, however, that, in agreement with most previous investigators, surface sea-water is supersaturated with respect to calcium carbonate, that equilibrium is established very slowly, and that the latter fact, together with the use of faulty methods or erroneous chemical constants, probably accounts for the great divergencies in the previously published data.

Since last year additional experimental studies have been made of a method for determining the chlorinity of sea-water more precisely than is possible with routine methods, and a paper describing it is now in press (J. Amer. Chem. Soc.). The method is intended for use in the preparation of "standard" sea-water and in investigations requiring greater accuracy than attainable with the usual more rapid methods. It differs from the Knudsen chloride titration method in that both the sample and the titrant ($AgNO_3$) are measured gravimetrically rather than volumetrically, and that the titration end-point is determined electrometrically, using silver-silver chloride electrodes and the Anderson-Hindman voltmeter. The resulting increase in precision is about tenfold.

Several of the reports dealing with results of the E. W. Scripps cruise to the Gulf of California in 1940 have been completed and one is nearing completion. C. A. Anderson, Professor of Geology, University of California at Berkeley, has submitted his manuscript on the geology of islands and neighboring land areas for publication by the Geological Society of America. Similarly, J. W. Durham of the International Petroleum Company has submitted his manuscript on megascopic paleontology and marine stratigraphy to the Geological Society of America. Within the next month F. P. Shepard expects to complete a manuscript on the submarine topography of the Gulf of California, which was mentioned in last year's report.

Two books on oceanography by members of the staff, manuscripts for which were completed prior to 1942, have been published as follows:

Oceanography for meteorologists, by H. U. Sverdrup, Prentice-Hall, New York, 250 pages, April, 1942.

The oceans: Their physics, chemistry, and general biology, by H. U. Sverdrup, M. W. Johnson, and R. H. Fleming, Prentice-Hall, New York, 1087 pages, December, 1942.

A new series, Records of observations, Scripps Institution of Oceanography, has been started. The first number of this series, "Oceanographic observations on the E. W. Scripps cruises of 1938," was published in July, 1942, and the next two issues dealing with observations in 1939 and in 1940 can be expected to be ready for distribution in 1943. In the first issue of this series are published tables showing interpolated values of temperature, salinity, and oxygen content at standard depths, and computed values of anomalies of specific volume and dynamic depth, as well as tables showing the number of diatoms at different depths in the surface layers. The next issue will also contain soundings and results of current measurements.

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GENERAL REMARKS ON PROBLEMS OF MILITARY OCEANOGRAPHY

H. R. Seiwell

(Abstract)

Not long after the initial declaration of a state of emergency it became obvious that extensive oceanographic services would be required by both the Army and the Navy. The shutting off of European sources of information and the increasing need for answers to specific oceanographic questions contributed to an aroused interest in this service. The rapid developments in technique of warfare have opened up numerous oceanographic problems, the answers to which are not readily available.

Present work in military oceanography is generally classified and specific references are, of necessity, omitted. In general, functions of military oceanographic organizations are divided into two main categories:

(a) To prepare oceanographic information for weather-forecasting over the oceans
(b) To prepare oceanographic information in a form for military operations

In addition, there is the intermediate operation of interpreting the effect of conditions of weather on specific oceanographic phenomena pertinent to military operations.

Forecasting conditions of weather over the oceans in wartime is beset with many difficulties and all pertinent information must be utilized. Unfortunately, the meteorological consequences of relationships between the circulation-patterns of the sea-surface and the energy given off to the atmosphere are imperfectly known. Investigations of this type are of the highest importance, and the consequences of combined air, land, and sea operation are frequently dependent on forecasts of fog, cloud, and other phenomena resulting from modification of air-masses by the sea-surface.

Preparation of reports of oceanographic characteristics of selected areas are concerned with specific operations. It is a well-known fact that, from the time of the initial reconnaissance until the completion of the operation, a detailed knowledge of tides, currents, bathymetric features, sea-swell, sea-surf, and sound-ranging conditions are essential in the selection of time and the type of equipment.

The question is frequently asked as to why oceanographic information required for military operations is not readily available. There are few specialists available who are competent to put this information in the proper form and give it an accurate military interpretation. Previous to the present war oceanographic work in this country was not concerned with the solution of military problems and, as a result, re-analyses of basic information are usually necessary. Furthermore, due to the ramifications of the present war, oceanographic information is frequently needed for remote regions of the Earth where little physical data of any kind are available. The problems of

military oceanography are far more difficult than the oceanographic problems of peacetime. It is to be hoped that as a result of experience during the present war, the foundations of military oceanography will be established and continue as an integral part of a future preparedness program.

Washington, D. C.

AMERICAN GEOPHYSICAL UNION

TWENTY-FOURTH ANNUAL MEETING

SECTION OF VOLCANOLOGY

REPORTS AND PAPERS

Washington, D. C.
April 23, 1943

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THE COMPOUND MERWINITE AND ITS STABILITY-RELATIONS IN THE SYSTEM CaO—MgO—SiO_2

E. F. Osborn

(Abstract)

Preliminary investigations on compositions between Ca_2SiO_4 and akermanite ($Ca_2MgSi_2O_7$), between merwinite [$Ca_3Mg(SiO_4)_2$] and akermanite, and between merwinite and monticellite ($CaMgSiO_4$) show that a field of merwinite appears on the liquidus surface of the system CaO—MgO—SiO_2, and that merwinite melts incongruently at 1575°C to Ca_2SiO_4, MgO, and liquid.

[The complete paper will be published in the Journal of the American Ceramic Society.]

Geophysical Laboratory,
Carnegie Institution of Washington,
Washington, D. C.

THE SOLUBILITY OF QUARTZ GLASS IN WATER

George C. Kennedy

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United States Department of the Interior)

(Abstract)

The solubility of fused quartz in water has been determined at the 300-atmosphere isobar for the temperature-range 200°C to 420° C. Some previous investigations of the solubility of silica in water have erred, it is believed, through a failure to distinguish true solubility from colloidal dispersion, combining in unknown proportions true solubility and colloidal dispersion. In the present determinations, solubility was measured by exposing a weighed charge of silica-glass to the solvent action of a known amount of water at a given temperature and pressure. At the end of the run the charge was again weighed and solubility determined by weight-difference. This general method of measuring solubility would seem applicable to any substance which shows little or no tendency to redeposit back upon the original charge by recrystallization from solution under the conditions of cooling.

Results of the present investigations indicate that the solubility of silica-glass in water is essentially zero at temperatures below 200°C and that it increases to a maximum of 0.20 part of silica per 100 parts water at 360°C. Solubility falls off beyond 360°C, but is only slightly less at the critical temperature of water.

Reconnaissance-determinations of solubility have been made at pressures up to 1,000 atmospheres and temperatures up to 500°C. These data strongly suggest that solubility in the gas-phase region is not only a function of temperature but is an inverse function of the specific volume of the water-vapor. At high pressures, as the density of the vapor-phase approaches that of the liquid, its ability to act as a solvent will approach that of the liquid.

U. S. Geological Survey,
Washington, D. C.

THE SYSTEM CaO—MgO—FeO—SiO_2: I--PRELIMINARY DATA ON THE JOIN $CaSiO_3$—MgO—FeO

J. F. Schairer and E. F. Osborn

(Abstract)

The join $CaSiO_3$—MgO—FeO is a plane through the regular tetrahedron representing the system CaO--MgO--FeO--SiO_2. This join cuts the primary phase-volumes of three interesting series

of solid solutions, namely, the magnesio-wustites (MgO—FeO solid solution), the olivines [monticellite ($CaMgSiO_4$)--iron-monticellite ($CaFeSiO_4$)], and the melilites [akermanite ($Ca_2MgSi_2O_7$)--iron-akermanite ($Ca_2FeSi_2O_7$)]. This join also cuts the primary phase-volumes of pseudowollastonite (α-$CaSiO_3$) and merwinite [$Ca_3Mg(SiO_4)_2$].

The complete paper will be published in the Journal of the American Ceramic Society.]

Geophysical Laboratory,
Carnegie Institution of Washington,
Washington, D. C.

HELVITE, A PRODUCT OF MAGMATIC EMANATIONS AT IRON MOUNTAIN, SIERRA AND SOCORRO COUNTIES, NEW MEXICO

Jewell J. Glass

(Published by permission of the Director, Geological Survey, United States Department of the Interior)

Introduction

The recent discovery of the widespread occurrence of helvite, a beryllium-bearing mineral, at Iron Mountain, New Mexico, has aroused interest in the commercial possibilities of a mineral which heretofore has been considered to have only scientific significance. Helvite contains about 13 per cent beryllium oxide as compared with five to ten per cent beryllium oxide in the mineral, beryl, which at present is the principal source of commercial beryllium. Helvite is consistently distributed, though sparingly in some places, through great masses of contact-metamorphic rock at Iron Mountain and, therefore, provides great hope for the future when the metallurgical problems have been solved and large-tonnage, low-grade ore can be utilized.

The contact deposits of iron and other metals at Iron Mountain have been known for many years, but it was not until November, 1941, when Lester W. Strock [see 1 of "References" at end of paper] discovered by spectrographic examination the presence of beryllium in helvite in the ores of Iron Mountain, that the attention of geologists was focused upon these deposits. Then, owing to rapidly increasing demands for beryllium metal in war materials, the Federal Bureaus, in 1942, undertook a detailed investigation of the deposits.

General geology

Iron Mountain is a high ridge that forms the north end of the Sierra Cuchillo in Sierra and Socorro Counties, southwestern New Mexico. It is located nine miles north of Winston (Fairview), the nearest town, and 50 miles northwest of Hot Springs, from which it can be reached over a fair gravel road (State Route 52).

The mountain, which is elongate north and south, is a narrow, tilted fault-block. It consists of Pennsylvanian (Magdalena) limestone and associated minor sandy and shaly beds which dip rather uniformly eastward. These sedimentary rocks have been cut by many dikes and plugs of rhyolite, and by younger sills and dikes of aplite and fine-grained granite, all of which are believed to be Tertiary in age (see Fig. 1). Magmatic emanations accompanying this igneous activity recrystallized the susceptible strata and locally formed iron-poor and iron-rich silicate rocks. Chief among the iron-poor contact rocks, which occur in the "zone of the light-colored silicates" of Hess and Larsen [2] are granulites. The iron-rich silicate rock, or tactite, is the ore-bearing rock in the region and is, therefore, of economic as well as scientific importance.

Two varieties of tactite are present at Iron Mountain; the more common variety is a massive magnetite-andradite rock, black to greenish or brownish color, formed through the replacement of limestone and representing the first product of magmatic emanations. Bodies of massive tactite range from a few inches to a hundred feet or more in width, and amount to hundreds of thousands of tons; the largest of these lies along the crest and high on the west slope of the Iron Mountain ridge.

The second variety is a conspicuously banded rock, to which the name ribbon-rock has been given. Ribbon-rock is a garnet-poor, magnetite-fluorite tactite. Layers of magnetite alternate with layers composed of fluorite and silicate minerals. Two distinct varieties of ribbon-rock

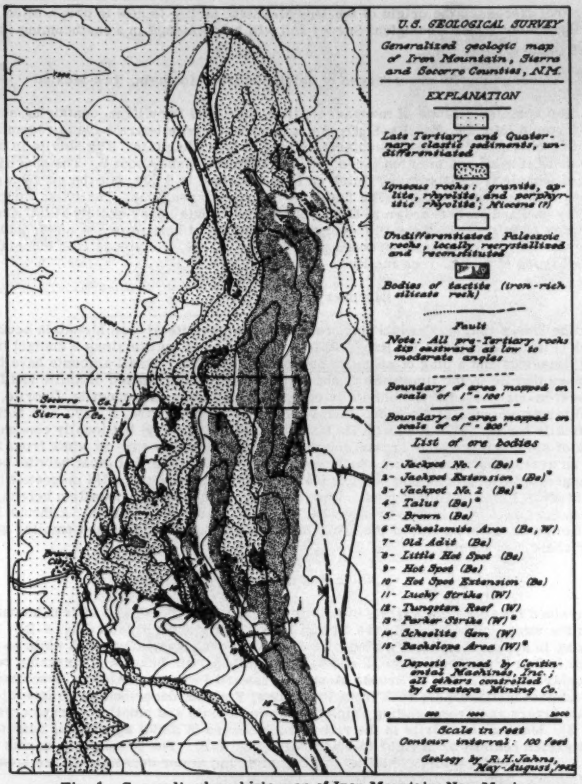
U.S. GEOLOGICAL SURVEY
Generalized geologic map of Iron Mountain, Sierra and Socorro Counties, N.M.
EXPLANATION
Late Tertiary and Quaternary clastic sediments, undifferentiated
Igneous rocks: granite, aplite, rhyolite, and porphyritic rhyolite; Miocene (?)
Undifferentiated Paleozoic rocks, locally recrystallized and recontributed
Bodies of tactite (iron-rich silicate rock)
Fault
Note: All pre-Tertiary rocks dip eastward at low to moderate angles
Boundary of area mapped on scale of 1" = 100'
Boundary of area mapped on scale of 1" = 200'
List of ore bodies
1- Jackpot No. 1 (Be)*
2- Jackpot Extension (Be)*
3- Jackpot No. 2 (Be)*
4- Talus (Be)*
5- Brown (Be)
6- Scheelomite Area (Be, W)
7- Old Adit (Be)
8- Little Hot Spot (Be)
9- Hot Spot (Be)
10- Hot Spot Extension (Be)
11- Lucky Strike (W)
12- Tungsten Reef (W)
13- Parker Strike (W)*
14- Scheelite Gem (W)
15- Buckskin Area (W)*
*Deposit owned by Continental Machinery, Inc.; all others controlled by Saratoga Mining Co.
0 500 1000 2000
Scale in feet
Contour interval: 100 feet
Geology by R.H.Johns, May-August, 1943
Sierra Co.
Socorro Co.
Brown City

Fig. 1--Generalized geologic map of Iron Mountain, New Mexico

occur at Iron Mountain: (1) A dark, beryllium-rich variety (Fig. 4-A) forms small bodies in Discovery Gulch, a narrow canyon east of Brown City (Camp headquarters) and on the west slope of the mountain about 0.3 mile north of Brown City; (2) a light-colored tapestry variety (Fig. 4-B) containing a small amount of beryllium-bearing minerals is widely distributed in the North End area. The largest bodies of it are exposed on the west side of the mountain and on the ridge-crest about one mile northeast of Brown City. The ribbon-rock bodies are more or less lens-shaped or finger-like; they trend parallel with the strike of the original beds and dip eastward with the beds. A distinct boundary can be seen between the ribbon-rock and the massive tactite and granulite, but the ribbon-rock grades imperceptibly into recrystallized limestone. Where ribbon-rock and massive tactite are both present, the massive tactite occurs between the ribbon-rock and the nearest intrusive contact; that is to say, the ribbon-rock lies between the massive tactite (Fig. 5) and the recrystallized limestone, farthest from the escaping magmatic emanations, in the zone of late-stage or hydrothermal action. The occurrence of helvite, beryllium-bearing grossularite, and beryllium-bearing vesuvianite in the ribbon-rock but not in the typical massive tactite may signify that beryllium-bearing minerals in contact-metamorphic deposits are limited to rocks of hydrothermal origin.

A paper that discusses the origin of the Iron Mountain tactite is now in preparation by Richard H. Jahns of the United States Geological Survey and will be published in a forthcoming issue of Economic Geology.

Description and occurrences of helvite at Iron Mountain, New Mexico

Helvite is a complex silicate of manganese, iron, zinc, and beryllium, containing some sulfur, and has the formula $(Mn, Fe, Zn)_4Be_3Si_3O_{12}S$. In general, helvite bears a close resemblance to garnet, and this characteristic is particularly evident at Iron Mountain. The helvite is isometric, and has tetrahedral habit and striated faces. It is brittle; hardness about 6. The specific gravity of an analyzed sample from Discovery Gulch on Iron Mountain is 3.334, but the specific gravity of helvite varies with the composition. The luster is vitreous to resinous. The color ranges from dark mahogany-red and amber-brown at Discovery Gulch to pale honey-yellow at the North End area. The index of refraction of the Discovery Gulch variety of helvite is n = 1.746; that of some of the North End variety is variable between n = 1.750 and 1.759. Helvite at Iron Mountain occurs in two distinct types of ribbon-rock tactite.

Discovery Gulch deposit

Most of the known coarsely crystalline, reddish-brown helvite at Iron Mountain occurs in Discovery Gulch (Fig. 1, Nos. 9 and 10, Hot Spot) in small bodies of tactite along a contact between recrystallized limestone and a plug of coarsely porphyritic rhyolite. Small amounts have been found in tactite lenses that lie in the limestone at and near contacts with masses of aplite and fine-grained granite. The iron-rich host for the helvite is composed uniformly of magnetite, fluorite, biotite, chlorite, and minor amounts of diopside. Garnet is absent or very rare, if any. The tactite is characteristically banded (Fig. 4-A) with its layers parallel and wavy, but locally concentric about an aggregate of solid magnetite or crystalline fluorite. These bands vary in width from 0.2 mm to 10 mm with an average of about 2 mm. Some consist of solid helvite, but most helvite-bearing layers are aggregates of fluorite and helvite; the intervening layers are solid magnetite or biotite-chlorite aggregates 3 mm to 10 mm thick. Irregular pods of coarsely crystalline helvite, with maximum dimensions 1 inch by 3 inches by 4 inches, are present but not common. Although helvite locally constitutes as much as half of the rock, it is generally present in much smaller quantities, even in the richest ore-sheets.

North End deposits

A fine-grained honey-yellow variety of helvite occurs on the North End of Iron Mountain relatively low on the west slope (Fig. 1) in the typical light-colored ribbon-rock (Fig. 4-B). This rock is very striking in appearance, having a reddish or dark green groundmass with white to pale yellow bands 0.1 mm to 3 or 4 mm wide (Figs. 2 and 3). The ribbon-rock bears a remarkable resemblance to the "orbicular-contact rock" of Brooks Mountain, Seward Peninsula, Alaska, described by Knopf [3], and to a contact metamorphic rock from Pitkäranta, Finland, described by Trüstedt [4]. In places the thin layers and cross-cutting veinlets contain fluorite and small scattered crystals of helvite (Fig. 3). Most of the helvite in the ribbon-rock occurs in small aggregates near the crystalline fluorite-rich centers or in fluorite-lined vugs (Fig. 4-B). The principal minerals in the ribbon-rock are magnetite, fluorite, biotite, and chlorite; and minor constituents are iron-rich amphibole, diopside, and hedenbergite.

Commonly the helvite is intimately associated with grossularite crystals, to which it shows striking resemblance and with which it is embedded in fluorite aggregates (Fig. 4-B). Field identification of helvite in the North End ribbon-rock is complicated by the indistinguishable characteristics of the two minerals. Indications of what appears to be replacement of the grossularite by helvite can be seen by staining the specimens. Isolated grossularite crystals from the North End ribbon-rock were examined by spectrograph and found to contain beryllium. A fibrous form of vesuvianite containing beryllium and boron occurs in the same rock-mass as the helvite, but has not been observed in the veinlets containing helvite.

Fig. 2--Photomicrograph of thin section of ribbon rock [crenulated structure pattern marked by alternate bands of magnetite (black), fluorite (white), and silicates (gray), plain light, X2]

Fig. 3--Photomicrograph of thin section showing veinlet of fluorite and helvite cutting the earlier formed ribbon rock [plain light, X2]

Fig. 4--Photograph of polished surface of two types of ribbon rock tactite at Iron Mountain, New Mexico: (A) Iron-rich, helvite-bearing tactite [(a) Lens of crystalline helvite with fluorite; (b) band of solid magnetite; (c) band of dark-colored silicates; (B) light-colored showy tactite [(a) Helvite and grossulariate crystals embedded in fluorite in a crystal-filled vug]

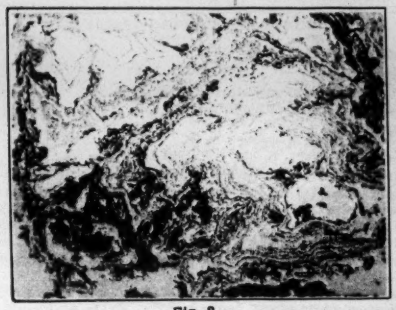

Fig. 2

Fig. 3

Fig. 4-A

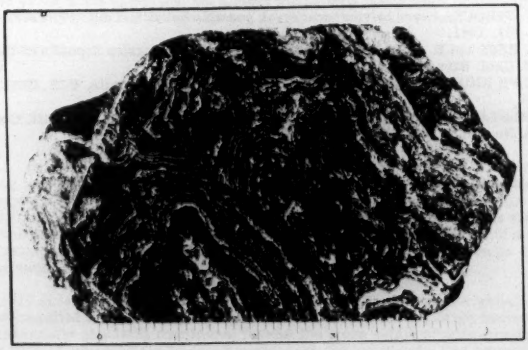

Fig. 4-B

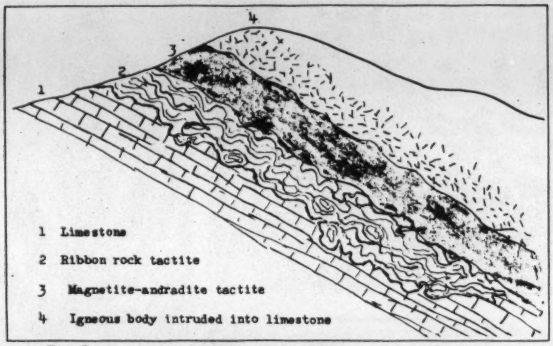

Fig. 5--Generalized section of the contact metamorphic zone at Iron Mountain, New Mexico

Since helvite at Iron Mountain occurs so consistently in ribbon-rock tactite, the conspicuous character of this rock may suggest the possibility of occurrences of beryllium-bearing minerals in other similar deposits.

Other occurrences

Helvite has been described from seven countries besides the United States, namely, Argentina, Australia, Canada, England (Cornwall), Finland, Norway, and Saxony; in the United States, it has been found in Colorado (two localities), New Hampshire, New Mexico, Massachusetts (two localities), Montana, and Virginia. As far as is known, New Mexico has the largest helvite-bearing area.

Helvite occurs in different rock and mineral associations; for example, three of the reported occurrences are in pegmatite, two in manganese silicate and carbonate veins, three in granites and gneiss (disseminated), and three in contact metamorphic rocks, whereas four are not stated in the literature. The three occurrences in contact-metamorphic rock are at Sierra de Cardoba (Argentina), Christiania (Norway), and Iron Mountain (New Mexico).

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U. S. Geological Survey,
Washington, D. C.

THE NICKEL DEPOSITS OF YAKOBI ISLAND, SOUTHEASTERN ALASKA

George C. Kennedy

(Published by permission of the Director, Geological Survey, United States Department of the Interior)

(Abstract)

Some of the large, low-grade nickel-copper deposits of Bohemia Basin, Yakobi Island, southeastern Alaska, which previously had been mapped and studied by the United States Geological Survey, were explored during parts of 1941 and 1942 by the United States Bureau of Mines. The Geological Survey interpreted the geologic features of the deposits as revealed by the work of the Bureau of Mines. The explorations were made largely by diamond-drilling. The three deposits most extensively tested are arranged around a small valley.

The oldest rocks of Yakobi Island consist of a thick sequence of volcanic rocks overlain by many thousands of feet of graywacke. These rocks were intruded by plutonic rocks, which were later sheared and metamorphosed, largely to albite granite gneiss and amphibolite. The nickel-copper deposits are segregations in norite bodies, which are parts of a post-metamorphic composite stock made up of norite, gabbro, diorite, and quartz diorite.

The deposits explored are parts of a norite body which contain pentlandite, chalcopyrite, and pyrrhotite. This norite body is surrounded by hornfels and gabbro. The sulfide-bearing parts of the body crop out near its periphery.

The diamond-drill holes indicate that the explored part of the norite body is basin-shaped. The sulfide-bearing rock forms a trough-shaped deposit lying at or near the lower contact of the norite.

The author is inclined to the belief that the sulfides, in the form of droplets, immiscible in the remaining magma, were concentrated by gravity in the lower parts of the norite body, at a time when most of the silicate minerals had crystallized. Although there is some local deuteric alteration of the norite, hydrothermal solutions are believed to have played little part in the emplacement of the sulfides, for no correlation could be established between the distribution of sulfides and the alteration of the norite. Likewise there is no correlation between the content of sulfides and fractures which cut the norite. This deposit has the same general features as the nickel-bearing basin-shaped noritic bodies of Insizwa (South Africa), Lancaster Gap (Pennsylvania), and several Norwegian localities.

If current attempts to class deposits of this type as hydrothermal, rather than as magmatic segregations, are to succeed, the lack of correlation between the position of the sulfides and the fractured or altered parts of the norite and the almost world-wide occurrence of the sulfide bodies in the lower parts of basin-shaped or trough-shaped noritic bodies, must be explained.

U. S. Geological Survey,
Washington, D. C.

EMPLACEMENT OF ADIRONDACK ANORTHOSITE

William J. Miller

In 1907 Cushing [see 1 of "References" at end of paper] published evidence that dikes of quartz syenite sharply cut the western side of the large Adirondack anorthosite body (or massif), thus indicating a distinctly younger age of the Adirondack syenite-granite series. He then also described an intermediate rock, lying without sharp contacts, between the anorthosite and the syenite, and gave reasons for believing that this rock was a product of assimilation or digestion of anorthosite by syenite magma.

Bowen [2] in 1917 advocated the consanguinity of the anorthosite and syenite-granite, arguing that the anorthosite resulted from settling of plagioclase crystals in a very large laccolithic body of magma under essentially standstill conditions, leaving the more acidic syenite-granite on top with more or less rock of intermediate composition between the anorthosite and syenite-granite. According to Bowen the anorthosite was never in a truly magmatic condition with intrusive power.

During the same year Cushing [3] vigorously maintained the distinctly younger age of the syenite-granite.

The next year (1918) the writer [4], in an elaborate paper, presented much more evidence in support of Cushing's ideas. Proof was given for the definitely younger age of the syenite-granite series, particularly the field evidence in many places where syenite and granite dikes and larger masses, often miles long, plainly cut into, and in part cut to pieces, the anorthosite. It was also then suggested that the syenite-granite and anorthosite may not have been greatly different in age, and that the solid anorthosite may still have been relatively hot when surrounded by, and partially involved with, the syenite-granite magma, thus facilitating local and variable development of intermediate rocks (Keene gneiss) by magmatic assimilation or digestion. In the same paper examples are given of well-defined dikes of anorthosite, proving its once magmatic condition, inclusions of Grenville in the anorthosite, anorthosite inclusions in the syenite-granite, and Grenville-anorthosite syntectics or mixed rocks. The writer then also suggested a modified, partial acceptance of Bowen's theory involving the origin of the anorthosite by settling of mafic crystals in a laccolithic or dome-shaped body of gabbroid magma, leaving a plagioclase-rich mass (anorthosite) between an upper and outer, chilled, gabbroid, border facies and underlying gabbro-peridotite, but excluding development of the syenite-granite from the same body of magma.

Kemp and Alling [5], in 1921 for the Mt. Marcy quadrangle, and in 1925 [6] for the Ausable quadrangle, definitely considered the syenite-granite series to be younger than, and intrusive into, the anorthosite. They also described inclusions of Grenville in the pure Marcy type of anorthosite, anorthosite-Grenville syntectics, and an intermediate rock produced by action of syenite magma upon anorthosite.

The writer [7] in 1929 stated that settling of mafic crystals "is not necessarily essential to an explanation of the origin of the Adirondack anorthosite" and suggested a gabbroid magma poor in possibility for development of mafic minerals so that the whole large anorthosite massif, with its gabbroic variations, as now exposed may have differentiated nearly in situ followed or accompanied by some magmatic flowage or movement before final consolidation. In this paper it is also proved that, in the Thirteenth Lake quadrangle, the syenite-granite series is distinctly younger than, and intrusive into, the anorthosite.

Buddington[8] in 1931 discussed at length the problem of Adirondack anorthosite, assuming a comagmatic origin of anorthosite, gabbro, syenite, and granite. Later, in 1936 [9] and 1939 [10], after making field observations in the eastern Adirondacks, he reversed his opinion and became convinced that the syenite-granite series is definitely later in age, and intrusive into, the anorthosite.

Cannon [11] stated in 1937 that a small body of anorthosite and related gabbro, in the Piseco Lake quadrangle, probably originated by gravity differentiation from a magma in a sill-like mass, but that the syenite-granite of the region is definitely later in age. He also described a metagabbro younger than the Grenville and older than the syenite-granite, but with age relation to the anorthosite uncertain.

Balk [12], in an elaborate paper in 1931, maintains that both the anorthosite and the syenite-granite series of the eastern Adirondacks differentiated from a parental magma while it was being forced upward to the southwest through the Grenville series in the form of a great sill or lens-like sill at an angle of about 20° and with a thickness of about ten or twelve miles. Again in 1933 [13] he definitely favors a lens-like or sill shape of the large Adirondack massif rather than a dome or a laccolith. He says that the anorthosite originated by some process of gathering and clustering of solid labradorite crystals which remained suspended a long time in the magma as it moved along. Movement of the crystals was not "governed predominantly by gravity," but a horizontal component of movement was more important than a vertical one. He argues at length that the syenite-granite series represents the "frozen mother liquor of the magma," thus making the anorthosite and syenite-granite comagmatic in origin. Balk's theory, unlike Bowen's, does not require the syenite-granite to be in a position always above the anorthosite.

According to Bowen's theory, the laccolithic body of magma from which both anorthosite and syenite-granite were derived must have been at least as large as the whole Adirondack region as indicated by the widespread distribution of both anorthosite and syenite-granite. Likewise Balk's sill, even if we consider only the two largest anorthosite bodies, must have been at least as extensive as all of the northeastern one-half of the Adirondack region, or fully 85 miles long and many miles thick. The field evidence indicates, however, that the two largest anorthosite bodies are separate intrusions of domical sill or laccolithic shape, usually cut into on all sides by the

syenite-granite, and also that the various outlying smaller bodies of anorthosite are either separate intrusions or inclusions in the distinctly later syenite-granite series.

Mention should now be made of the important fact that, in addition to the very large Adirondack anorthosite massif, outlying masses are known in the Thirteenth Lake, Blue Mountain, Schroon Lake, Lake Pleasant (there mapped as "basic syenite"), Piseco Lake, Russell, Carthage, Lyon Mountain, and Mooers quadrangles. Anorthosite is, therefore, very widespread in the Adirondacks with outcrops ranging from the western edge to Lake Champlain, and from the northeastern edge into the southern part, in each case more than 100 miles. There is no evidence whatever of either a laccolith, dome, or sill with dimensions as great as the whole Adirondack region. Instead of such a single extensive body, it might have been argued by both Bowen and Balk that there were various large and small laccoliths, or sills throughout the Adirondack region in each of which magma body anorthosite and syenite-granite formed. But, even so, how are the widespread distribution, tremendous volume, general discordances of primary structures, and the distinctly younger age of the syenite-granite in relation to the anorthosite to be explained? Buddington [10] says: "The volume of quartz syenite and granite is so large as compared with the gabbroic rocks that the latter are wholly inadequate to yield the former by differentiation."

Bowen's theory of gravitative crystal settling requires a practically standstill condition of the laccolithic magma. Balk's theory requires plagioclase crystal gathering or sorting, with crystal settling a minor factor in a great sill-magma while it was moving scores of miles. The only important similarity between the two theories is that each explains both anorthosite and syenite-granite as direct derivatives of single magma. For reasons already referred to, and others to be given, the writer believes that neither theory is satisfactory. One may wonder why Balk [13] says "that most of Bowen's arguments are supported by an abundance of field observations."

Balk's 1931 map [Plate XI] is presented as evidence that the main anorthosite massif is a sill or lenticular mass dipping about 20° to the north-northeast. But is not the structure indicated on this map just what would be expected in the case of a domical sill or laccolithic body with primary foliation dipping generally outward on all sides, especially in its border portions?

The writer in 1929 [7] shows that the second largest Adirondack anorthosite body, located in the Thirteenth Lake quadrangle, has a domal (or possibly laccolithic) structure with quaquaversal foliation dips of 15° to 45° around it. But Balk summarily dismisses this important case (p. 333) merely by suggesting that it is "a lens which dips gently in a northward direction." It is important to note, in this connection, that similar domal structures also occur in the syenite-granite series, a particularly fine, large example being the Snowy-Panther Mountain dome described in the writer's report [14] on the Blue Mountain quadrangle. This is certainly not a sill intruded at a low angle.

Balk's theory requires the comagmatic origin of anorthosite and syenite-granite. As strong supporting evidence he says that primary foliation dips and pitch of flow-lines in the border portions of both the main anorthosite massif and the adjacent syenite-granite are significantly parallel, constituting "one uniform dynamic system which disregards the nature of the rock." The present writer dissents from this statement because many field facts do not support it. Strikes and dips of primary foliation in the anorthosite and syenite-granite are by no means always parallel, certainly not with such uniformity as indicated on the map [Plate XI]. Foliation strike and dip observations recorded on the writer's Lake Placid [15] and Schroon Lake [16] quadrangle geologic maps, and on Cushing's Long Lake map, do not support Balk's mapping in those regions. These and other (unpublished) observations were made before Balk's theory was advocated. Some cases of parallelism of primary foliation in border portions between anorthosite and syenite-granite are fortuitous. In other cases crude parallelism may have resulted from some tendency of the syenite-granite magmatic currents to be controlled by pre-existing Grenville structure around the dome or laccolith, or by frictional drag in the syenite-granite magma where it moved close to the anorthosite massif.

Balk's other 1931 map [Plate XII], showing strike and pitch of flow-lines as evidence of comagmatic origin of anorthosite and syenite-granite, is even less convincing than his primary foliation map. In only a few places are the flow-lines shown to be parallel across the boundary, in other places there is definite discordance, and in most places flow-line directions are shown only on one side of the boundary between anorthosite and syenite-granite. Some crude parallelism of flow-lines would be expected for reasons above given in the discussion of parallelism of foliated structures, but this is no proof of comagmatic origin of anorthosite and syenite-granite.

Important evidence is presented at length by Balk to prove that both foliation and widespread

granulation in the anorthosite are primary features, indicating a former truly magmatic condition of the anorthosite. This confirms the writer's conclusion published 13 years earlier (1918).

Balk maps large and small "swirls" of magmatic origin predominantly in the northeastern one-half of the main anorthosite massif [12, Plate XI]. In a number of these swirls strike and dip of primary foliation almost box the compass. This type of structure was recognized a good many years earlier by the writer [22 and 15, p. 67], who stated that sharp variations in degree of granulation and primary foliation, as well as in strike of foliation, occur on large and small scales in both the syenite-granite and anorthosite series, and that such variations were produced by varying (or swirling) magmatic currents during a late stage of consolidation. Similar primary structures also no doubt occur within the southwestern one-half of the main anorthosite massif, but most of this area is left blank on Balk's map [Plate XI] probably in part because such structures are less evident in this generally purer, more plagioclase-rich facies of the anorthosite. A possible explanation is that this part of the anorthosite resulted from more uniform intrusion of a stiffer or less fluid magma which was involved with little or no Grenville and thus not so subject to a less forced differential flowage. One may wonder, however, if this wildest and most difficultly accessible region in the whole Adirondacks was examined in sufficient detail to get the structural facts. In some parts of this region, where the anorthosite is by no means devoid of foliation, the writer has seen variable primary structures. Stephenson [17] has very recently (1942) found swirls of magmatic origin well within this region in the Lake Sanford district. Further field work will doubtless reveal others. The evidence is, then, plain that the main anorthosite massif was once a true magma in which pronounced irregular currents or movements occurred. In this important respect Balk and the writer are in agreement.

In regard to the primary foliation of the anorthosite, another point needs emphasis, namely, the steepness of the dips. Balk's theory requires generally low dips in both anorthosite and syenite-granite. He says that primary foliation and flow-line dips are seldom more than 30° in the anorthosite, the only good exception being northeast of Lake Placid. But there are many exceptions to this statement. A few widely scattered examples of steep dips in the anorthosite are as follows: Between Lewis and Elizabethtown, 45°-70°; vicinity of Franklin Falls, 25°-70°; northeastern corner of the Ausable quadrangle, 25°-65°; and five miles north of Schroon Lake village, 40°. These and many other relatively steep primary foliation dips, together with the magmatic flow-structure swirls, indicate strongly that the anorthositic magma rose at a much higher angle than advocated by Balk. It should be stated, however, that primary foliation within the large massif, and especially within its border portions, are, as a rule, distinctly less steep than they are within the Adirondack syenite-granite series in general. Such discordance does not bear out the idea of comagmatic origin of anorthosite and syenite-granite. There is a tendency not only toward greater concordance of primary dips in the border portions of both rocks for reasons already given, but also toward lower dips in the syenite-granite just around both the main anorthosite massif and the smaller Thirteenth Lake quadrangle body. Such lower dips are believed to have resulted from considerable directional control of the syenite-granite magma by the pre-existing relatively low-dipping Grenville strata resting upon the flanks of the anorthosite domes or laccoliths. Within the syenite-granite, a few miles or more from the two larger anorthosite bodies, the story is, however, very different as will now be shown.

Balk says [12, p. 393] that, on the writer's maps, not enough foliation strike and dip signs, and hardly any figures indicating amount of dips, are plotted for the purpose of showing the structure of the syenite-granite series. This same criticism may be applied to his own map [Plate XI] on which dip figures are not given and dip directions are largely generalized with many important exceptions to his plotting of the symbols known to the present writer in both the anorthosite and the surrounding syenite-granite. Balk does state in his text that dips are very rarely more than 30°, with only one important local exception. The writer also, in each text accompanying various geologic maps, plainly states that primary foliation dips vary in amount and direction, but that relatively steep dips greatly predominate. Thus on each of the following quadrangle maps 100 to 200 strike and dip symbols, selected as fair representatives from many other field observations, are plotted: Lake Placid [15]; Schroon Lake [16]; Blue Mountain [14]; Thirteenth Lake [7]; Lake Pleasant [18]; North Creek [19]; Luzerne [20]; and Lyon Mountain [21]. Dip figures are given on the last named. In all of the quadrangles mentioned it is quite the rule for dips--most of them being in the syenite-granite--to be steep with by far most of them ranging between 30° and 90°. On Cushing's Long Lake map [1], dips also vary widely with many of them much steeper than 25° Primary foliation dips in the syenite-granite series are, therefore, distinctly steeper than those in the anorthosite, indicating a general structural discordance in this respect, and out of harmony with Balk's theory.

Another significant feature is the arrangement of the primary foliation of the syenite-granite

series in the form of sweeping curves or "swirls" on large and small scales. This was pointed out by the writer in 1916 [22] which includes a description of the Panther-Snowy Mountain mass in the Blue Mountain and Indian Lake quadrangles. Cannon [11] has described the Piseco dome. It is now evident that primary foliation swirls are common in the Adirondack syenite-granite series. Such structures, with steep dips common, are not in line with Balk's theory.

Balk's low-dipping lenticular sill requires a floor. He makes a labored effort to prove that there is such a floor of involved Grenville a'. syenite-granite forming a belt on the southwestern side of the main anorthosite massif. He says that foliation along the main axis of this belt is vertical; that it dips south-southwest between the axis and the anorthosite; and that it dips north-northeast to the south of the axis. This he calls a fan structure [12, p. 329]. Among various field facts opposed to this interpretation are the following: The axis extends east-west in general and not parallel to the border of the anorthosite massif; dips are north, not south, in the very critical area north of the axis, that is, throughout the middle-western part of the Schroon Lake quadrangle as shown on the writer's geologic map; and no observations at all are plotted [Plate XI] in a large part of the Newcomb quadrangle north of the axis, but, on Balk's geologic map of the quadrangle [23] irregular swirl structures are indicated. The greatest deviation of the axis from parallelism with the anorthosite border is in the Blue Mountain quadrangle where it bears west-southwest. Furthermore, the foliation strike, instead of being so uniformly nearly east-west across the southern parts of the Blue Mountain and Newcomb quadrangles, is strongly curved around the noses of the Indian Lake and Thirteenth Lake domes. Buddington [10], for still other reasons, opposes this fan-structure theory.

The writer finds it impossible to see how much, if any, of Bowen's crystal-settling theory can be retained in application to Balk's conception of a tremendous sill-magma moving forward and upward at a low angle for a distance of fully 100 miles! Again, if we accept the idea of such a tremendous sill, how can the similarity of the anorthosite and its facies, throughout a distance of 100 miles, be explained? True anorthosite with gabbroic facies occur in nearly all of the widely scattered anorthosite bodies in the Adirondack region. Balk believes that the magma continued to differentiate as it moved for a long time. Under such conditions, the finished products would surely be distinctly different in such widely separated parts of the sill.

It is fundamental to Balk's theory that anorthosite, gabbro, and syenite-granite are comagmatic in origin, and that they exhibit gradational zones from one to another. A similar relationship between anorthosite and syenite-granite is also fundamental to Bowen's theory. More or less elaborate field evidence to the contrary has been presented by Cushing first in 1907 [1], the writer in 1918 and 1929 [4, 7], Kemp and Alling in 1921 and 1925 [5, 6], Buddington in 1936 and 1939 [9, 10], after reversing his previous (1931) view, and Cannon in 1937 [11]. It is here unnecessary to review this abundant and convincing evidence for the distinctly younger age of the syenite-granite which Balk [12] practically throws out of court by saying briefly that "dikelets, so-called dikes, and supposedly cross-cutting veins of syenite in the anorthosite may just as well be interpreted as expelled portions of mother liquor."

Transitional or gradational rock between, and comagmatic in origin with, anorthosite and syenite are required by the theories of both Bowen and Balk. Other workers, however, believe that such a rock is not always present, that it is relatively not large in amount, that it often also occurs between anorthosite and granite, and that it is not comagmatic with anorthosite and syenite-granite. They interpret this rock as a mixed gneiss or syntectic produced by action of syenite or granite magma upon solid anorthosite. Cushing [1] first gave such an explanation for the occurrence in the Long Lake quadrangle in 1907, and the writer [4] in 1918 presented elaborate and amplified evidence from the eastern Adirondacks in support of Cushing's view, and he called the transitional or mixed rock "Keene gneiss." Since then Kemp and Alling [5, 6], Cannon [11], and Buddington [10] have been in essential agreement with Cushing and the writer. The important published data need not be repeated here.

An important problem is whether the main anorthosite massif has a chilled gabbroic border zone. Cushing [3], Bowen [2], the writer [4], and Buddington [10] all favor this interpretation, the writer having called the chilled border rock the Whiteface anorthosite. Balk argues against this interpretation. In view of the facts that favorable evidence has been published at length, and that Buddington [10] has satisfactorily answered Balk, further discussion seems unnecessary here. A chilled zone, including both an outer and upper border such as the Whiteface anorthosite, would be difficult to imagine on the basis of Balk's theory.

Nearly all workers on Adirondack geology have been troubled about the number, age-relations, structure, and origin of Adirondack gabbros and metagabbros. Certain of these occur in numerous,

relatively small bodies not only in the eastern anorthosite area, but also throughout the Adirondacks. These will be referred to as Group 1. Certain other gabbroic rocks, which are plainly facies of the anorthosite series, will be referred to as Group 2. Certain amphibolites and so-called "metagabbros," genetically related to the Grenville at least in part, are not included, as for example Balk's so-called "gabbros in statu nascendi" which Buddington believes are mafic rocks produced by action of anorthosite magma upon limy Grenville.

The gabbros and metagabbros of Group 1 often contain olivine, and Buddington calls them undersaturated gabbros. Most of them have oval or round ground plans, suggesting cross-sections of stocks with dimensions ranging from a few yards or rods to several miles. They occur within areas of Grenville, anorthosite, and syenite-granite. Very commonly they have strongly foliated amphibolitic border zones around massive interiors. Many of these gabbros are shown on Balk's 1931 map [12, Plate XI] and by him called "spherical gabbros."

Cushing in 1905 [1], Kemp and Alling in 1925 [6], and formerly the writer have considered these gabbros to be younger than the syenite-granite series. Field work on the Lyon Mountain quadrangle in 1918 [21], Luzerne quadrangle in 1920 [20], and the Thirteenth Lake quadrangle in 1923 [7] convinced the writer that such gabbros are all, or nearly all, older than the syenite-granite. This interpretation is in agreement with both Balk and Buddington.

At some length Balk [12] interprets the above described undersaturated gabbros ("spherical gabbros") as crystal accumulations or segregations which developed in the same magma from which both anorthosite and syenite-granite also differentiated while the parental magma was slowly moving many miles as a great sill. He maintains that these sphere-shaped gabbro bodies rest on saucer-shaped floors of anorthosite or syenite with gradations downward, through highly foliated border zones, from the gabbro into the syenite or the anorthosite. According to Balk, the foliation commonly dips toward and under the spherical gabbro on all sides.

According to Buddington, however, these undersaturated gabbros should not be confused with the saturated gabbros of Group 2 which latter very commonly occur as facies of, and are comagmatic in origin with, the anorthosite. He says [10, p. 215] that the undersaturated gabbros "form a discrete group with no gradational relationship to the (saturated) anorthositic rocks."

In regard to the gabbros of Group 2, Buddington [10, p. 215] says that "there are all gradations between anorthosite and saturated gabbros," that "in many examples the more mafic facies show definite intrusive relationships to the prevailing less mafic types," and that "the order of succession indicated is definitely from anorthosite to saturated gabbro or norite." These saturated gabbros of the anorthosite series contain the titaniferous magnetite ore deposits.

According to Buddington [10, p. 64], there are also very mafic metagabbros in part genetically related to the undersaturated gabbro series of Group 1, and in part to the gabbroic facies (Group 2) of the anorthosite series.

Mafic metagabbro, rich in titaniferous magnetite, occurs locally as conformable bands or discordant dikes within metagabbro where the latter is closely associated with the main anorthosite massif. Stephenson [17], in his paper on the Lake Sanford region, says: "The Cheney Pond ore body is a lens-like conformable mass of ore which occurs in a spherical gabbro body similar to those described elsewhere in the Adirondacks by Dr. Balk. This body grades into gabbroic anorthosite to the east of Cheney Pond, but intrudes anorthosite on the southwest side." Here then, the gabbro body and anorthosite seem to be practically contemporaneous.

Cannon [11] describes a small area in the Piseco Lake quadrangle in which hypersthene gabbro and olivine norite are closely associated with anorthosite and are younger than the syenite-granite. He favors the idea that these rocks are essentially comagmatic in origin, but says that "these mafic rocks may be intrusive into the anorthosite." If the former, it is a case of undersaturated (olivine) gabbro comagmatic with anorthosite. Cushing [1], in the Long Lake quadrangle, found gabbro dikes cutting anorthosite, and also some evidence of gradation between anorthosite and gabbro. In the Schroon Lake [16] and Lake Placid [15] quadrangles, the writer found evidence that the undersaturated gabbros are younger than the anorthosite, but, in the Lyon Mountain quadrangle [21], some small anorthosite dikes were found cutting a gabbro.

Fine large examples of olivine gabbro bodies (Group 1) with prevalent ophitic texture, local variations to foliated metagabbro, and in contact with the main anorthosite massif are the Peaked Hill (Paradox Lake quadrangle) and the Texas Ridge and Cheney Pond (Schroon Lake quadrangle) occurrences. In each of these cases the undersaturated gabbro cuts, or contains inclusions of,

the anorthosite, thus indicating a younger age of the gabbro. Ogilvie [24], Buddington [10], and the writer all agree on this interpretation for the Peaked Hill gabbro which Balk describes [12, pp. 341-343] as a fine large example of a "spherical gabbro" resting on a saucer-shaped floor of anorthosite and comagmatic in origin with it.

Mineralogically, an important, almost universal, difference between the gabbros of Groups 1 and 2 is the presence of olivine in many of those of Group 1. But more than one-half of the described examples of Group 1, especially the metagabbros, do not contain modal olivine, while in a few cases olivine is known in the gabbros of Group 2. In the writer's opinion, this suggests a modified genetic relationship between the two groups. Buddington's explanation (personal communication) is that the olivine of Group 2 is a hortonolite variety and not the normal forsterite-rich olivine of saturated gabbros. Augite is nearly always important in both groups, and hypersthene and hornblende often occur in varying amounts.

In regard to the composition and age relations of the gabbros (including metagabbros) of Groups 1 and 2, the evidence just presented seems somewhat confusing. This confusion may be obviated by considering two gabbros (Groups 1 and 2) as advocated by Buddington, but they may or may not be as distinctly different in age as he believes. It is possible that the gabbro of Group 1 is only a little later than the anorthosite or its gabbroic facies (Group 2), representing intrusion of a very late differentiate of the same general parental magma which gave rise to the anorthosite series, or from a source still deeper in the outer shell. Intrusion of such a differentiate into the earlier, largely or wholly, solidified, saturated anorthositic rocks would explain the occasional close association of the undersaturated gabbro and the saturated anorthosite series.

After the emplacement of the anorthosite series and the gabbro of Group 1, tremendous volumes of syenite-granite magma invaded, and more or less cut to pieces the widespread Grenville, anorthosite, and gabbro of Group 1 in the Adirondack region. Numerous large and small masses of Group 1 gabbro now occur in the form of inclusions in the syenite-granite with oval or elongate ground-plans simulating stocks or sheets.

Few, if any, gabbro masses of Group 1 occur well within the main anorthosite massif excepting in the northeast. This is probably because the very thick massive portion of the anorthosite resisted intrusion, while its thinner northeastern portion, as well as the extensive weak Grenville country rock, permitted much easier entry of the gabbro magma. In the border portions of the anorthosite (for example, Newcomb, Schroon Lake, Paradox, and Elizabethtown-Port Henry quadrangles) the gabbro bodies of Group 1 are generally larger because they there show more nearly their original size having been little, or not at all, cut to pieces by the syenite-granite.

The border-zone foliation, emphasized by Balk as so commonly found between gabbro bodies of Group 1 and country rocks, is here regarded as partly primary, but mainly secondary, in origin. In 1914 [19] and 1916 [22] the writer believed that the foliation of these gabbros, then supposed to be stocks younger than the syenite-granite, was largely or wholly primary. Since 1923 [20] he has recognized both primary and secondary foliation, the latter especially in the border portions of the gabbro bodies. It is well known that very local primary differences in composition and foliation are common in gabbros. Such primary foliation in these gabbros may have, in some degree, controlled and caused accentuation of the secondary foliation. In any case, the writer now believes that the foliated borders of the gabbros of Group 1 within the syenite-granite series is very largely secondary in origin and caused by pressure and stress applied at the time of intrusion of the syenite-granite magma during a late stage of magma consolidation. It is possible that some pressure continued after the magma solidification. In many places, however, highly foliated and amphibolitic borders of the gabbro bodies are cut, and even injected lit-par-lit, by syenite or granite. This proves that much or all of this foliation was produced before final consolidation of the syenite-granite magma. For this reason the writer cannot follow Buddington who, in a personal communication (March, 1943), believes that the gabbro foliation was, in large part, "due to differential movement in the zone between two solid rocks--gabbro on the one hand and anorthosite or syenite on the other hand," the regional pressure having come distinctly later than the intrusion of the syenite-granite series or at the time of intrusion of a stiff later pink granite. The writer doubts whether any considerable amount of pink granite is so much later than the syenite-granite series. In any case pink granite in many places shows the same relation to the gabbro as the syenite, even injecting foliated borders of the gabbro.

Gabbro bodies of Group 1 wholly or partly within the anorthosite are usually not so strongly foliated and syenite or granite is always close by. In such cases, the border foliation is probably in part primary, but mainly produced secondarily by stresses applied during intrusion of the syenite-granite.

From the above discussion it seems clear that both Bowen's and Balk's theories fail, in certain fundamentally important respects, to stand the test of field evidence. The writer's 20 conclusions listed at the end of his elaborate 1918 paper [4] have stood the test much better. Certain of these conclusions were reached by Cushing still earlier and much amplified in the 1918 paper, while many of them were there presented for the first time. Some modifications of a few of the conclusions of 1918, in the light of later field evidence and discussions, may be suggested as follows: (1) Instead of a typical laccolith, the main anorthosite massif may have the shape of a steep-dipping domical sill. In either case it was an asymmetric body with various local domical structures in its upper portion as indicated by the "magmatic swirls," and with a prominent, relatively thin portion extending northeastward as strongly suggested by the fact that this part of the massif has been cut by so many undersaturated gabbro bodies, and by so much syenite-granite. The Thirteenth Lake anorthosite seems to be laccolithic or domical. Some of the smaller occurrences may possibly be sills or lenticular masses. (2) The anorthosite series magma in general was even more active and freer to flow than formerly advocated as proved by the primary foliation "swirls" shown on Balk's map [12, Plate XI]. (3) The significance of the many, relatively small, widespread "spherical gabbros" of Balk, or the "undersaturated gabbros" of Buddington, were not discussed in the 1918 paper. Even now there is some question about them, but they do not necessarily affect the general 1918 conclusions in regard to the origin and emplacement of the anorthosite. (4) Did the gabbroid magma differentiate practically in situ by settling of mafic constituents, leaving the anorthosite as an upper, residual mass? There may have been more or less gravitative sorting of plagioclase crystals in gabbroid magma at considerable depth followed by further differentiation, probably filter pressing, during or after emplacement higher up in the outer shell of the Earth, or both.

Early deformed plagioclase phenocrysts and protoclastic texture in the anorthosite indicate strongly that filter pressing was active. Stephenson [17], for the Lake Sanford region, believes "that gabbroid interstitial magma (was) being pressed from the mush of the accumulated plagioclase crystals as the anorthosite was being emplaced."

The large and small bodies of anorthosite, so widely scattered throughout most of the Adirondack region, must have been derived from a common general source, just as the widely distributed and still more extensive syenite-granite series no doubt came from another source. In this connection Buddington [9] suggests the possibility that the magma from which the anorthosite was derived resulted from partial melting of a gabbroid anorthositic shell in the lithosphere.

One may speculate upon a possible derivation of both the anorthosite and syenite-granite magma from a still earlier, common magma, but, if so, such differentiation must have occurred far below the present surface, and the two differentiates must have moved upward at different, though possibly not widely separated, times with still further differentiation of each magma taking place meantime and even after coming almost to rest.

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CLASSIFICATION OF LAVA-SURFACES

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Field study of the Modoc Lava Beds in northern California suggest that the simple grouping of the three forms of lava-surface as aa, pahoehoe, and block, might well be expanded. The surfaces studied appeared to be of the same general appearance and quality as similar surfaces studied near Mt. Lassen to the south, and on the Hawaiian Islands. Though there should be some common ground of understanding, there is still some doubt and confusion as to what is pahoehoe and what is aa. Most geologists, who accept the terms, will say that pahoehoe is smooth and that aa is rough, and that is correct as far as it goes. During the field study it was noticed that there was a gradual scaling down from very rough or rugged aa to considerably less rough aa. Though still far from smooth, this aa was much less coarse. In one case these aa projections were found arranged in rows or ropes about six inches apart and it appeared probable that a ropy structure had become aa along the crests. Furroughed aa describes this somewhat unusual lava-surface. Curiosity was aroused as to where the line of division between the two types of surface might be, and the field study was modified accordingly. Two methods of attack were adopted, actual measurement and general appearance. In making the measurements, the relief of the points with respect to the cavities was the portion tested (Fig. 1). Except for the glazed surfaces in lava-tubes and vents, the outer vesicles were not sealed over, leaving the so-called smooth pahoehoe quite rough to the touch. If there were no other projections close by, the relief of the surface would be a little less than that of the diameter of the vesicle. Such measurements as were made on pahoehoe were about equal to, or less than, one mm.

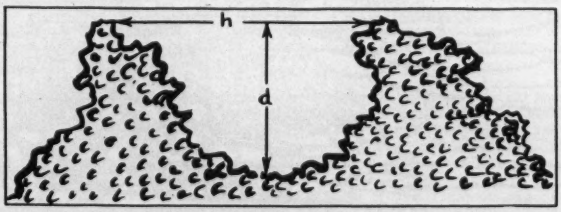

Fig. 1--Method of measuring for degree of roughness of lava

A single slab of lava was found near the southeast corner of the Lava Beds National Monument, about a third of the way between Blue Eyes Point and Caldwell Butte, and perhaps a quarter of a mile east of the road. This slab was pahoehoe over approximately a half, while the other half was too rough to be called pahoehoe and was accepted by the writer as the representative of the finest size of aa, and the measurements were incorporated into the table. Inspection of the slab showed that the surface changed from an ordered arrangement of vesicles with accordant cuspoidal edges on the pahoehoe side, to a slight disarrangement of vesicles with knobs and slight projections of the aa-surface.

When the beaded edges of these vesicles were even, they formed a relatively smooth surface that passed as pahoehoe. When they were uneven, they began to be too rough for pahoehoe and resembled aa. On the pahoehoe-surface the vesicles were so often elongated to ovals that it suggested that they congealed under tension. Contrarily it could be true that aa cooled under very local compression. More probable, it was differential cooling under distortion. This would explain why aa-lava is usually found at some distance from the vent, where there has been some chance for flow over a rough channel or rough terrain to place the surface under alternations of tension and compression while cooling [A. E. JONES, The formation of basaltic lava-flows, J. Geol., v. 45, No. 8, 1937]. Rougher lavas than those of one mm were generally those whose roughness was composed of more than vesicles. These measurements were made where distance (h) from point to point was about the same as the depth (d) between the points (Fig. 1). This is a crude form of measurement, and yet it appeared adequate and very applicable in the field. Where these measurements ranged from one mm to one cm (less than one-half inch), the surfaces appeared much rougher than nearby pahoehoe and in the classification it is designated fine aa.

A further distinction is that the pahoehoe presents an ordered area of vesicles with accordant cuspoidal, sometimes beaded rims; while aa is so disordered as to be hard to describe, the vesicles apparently having sharper rims, the whole being a very hummocky uneven surface. As texture is often thought of as something that can be demonstrated on a hand sample, here it gets rapidly out of hand for medium-aa ranges up to one decimeter in its dimensions, while gross-aa often has dimensions of a meter or more. It is probably better to refer to it as a smooth or rough surface, rather than texture. Also, it is wished to retain structure as a term applicable to the body of the flow; designating strong, or massive structure in contradistinction to weak or loose structure.

In arranging the table of classification, the lava of the smoothest surface was placed at the left with the very rough kinds at the right. Also, the more massive and structurally solid lavas were placed at the top, becoming progressively weaker toward the bottom. In the upper left-hand corner was then placed the very massive lavas with pahoehoe-surfaces that are fairly common in and about Kilauea Crater. These lavas are hummocky with tumulii or pressure-domes (see Fig. 2),

Fig. 2--Idealized drawing, illustrating classification of lava-surfaces

Table 1--Classification of lava-flows

Weak loose structure to solid structure	Ordered smooth surfaces	to	Rough disordered surfaces
Glazed surfaces found inside caves, bubbles, and vents along with drip pendants and flow-lines	Massive pahoehoe of very thick cross-section (10+ feet) with hummocks or tumulli, and with cracks at infrequent intervals		Ropy lava (on surfaces, slabs and blocks) fine smooth ropes to coarse rough ropes (1 to 6 inches) formed by folding of viscous surfaces due to the drag of underlying mobile lava (grades to furroughed aa)
	Scaly pahoehoe thin (one-quarter to one foot) small flow-units overlapping like scales, but solid, may show pillows and toes		Aa-lava in place Fine-aa: 0.1 to 1 cm, < 1/2 in. Medium-aa: 1 to 10 cm, 1/2 to 4 in. Gross-aa: 10 to 100 cm, 4 to 40 in.
	Shelly pahoehoe thin bubbles of weak structure (one-half foot) that break into slabs and plates of loose structure = slab-lava		Aa-rubble of fragmental scoriatious character, few fractured surfaces (grades from rubble to aa-clinker)
			Block-lava usually four to five fractured sides (grades in size from one-half foot to 10+ feet)

but not in the same manner as an aa-flow is hummocky. There are a few contraction cracks at intervals of many feet or meters, and the general average thickness, though often unknown, might range from 5 to 50 feet, or more. The margins may be as thin as one or two feet, increasing rapidly in thickness towards the body of the flow.

Next below was placed the lava that is composed of thin overlapping flow-units, rather tightly placed together, thickness at the edges is to be measured in inches rather than feet, and the widths across the flow-units may range from 10 to 100 feet. Such a lava-formation has been noted several miles south of Kilauea Crater, and a mile or so west of Puu Ohale, along the Puna-Kau trail; suggested name scaly pahoehoe. Under this was placed the equally thin, more fragile shelly pahoehoe found near the summit of Mauna Loa, and in some of the recent small flows in the Modic Lava Beds, on the rifts a mile or so north of Black Crater. No room has been made for the thin flows of Mauna Iki, near Kilauea, or similar flows about Fleeners Chimneys in the Modoc Lava Beds, though they might be considered as being between the above scaly and shelly types. This shelly lava is in domes or bubbles several feet across and with a roof thickness of one to three inches; it will often break under slight weight, displaying the interiors of the domes, which may be as much as three feet in depth. When this shelly pahoehoe is badly broken, it may be called slab-lava [probably suggested by R. L. Nichols]. Though this slab-lava is a form of block-lava, it has been entered in Table 1 under shelly pahoehoe, and in the long run it may prove to be more prevalent than shelly pahoehoe though the writer noted them together in the field.

As a part of pahoehoe, though rougher, the ropy form is placed at the upper right of the classification-table. It is less frequently found and is formed in small fans where lava has flowed under a thin partly congealed surface, causing it to fold into regular small ridges (see Fig. 2). These ridges or ropes may be from one to six inches in diameter and an equal distance apart. Since they are retarded at the edges, they have been curved so that the convex side is downstream. The ropes may be several feet long, and the curvature approximates the large part of a circle. They are not usually found at the margin of a flow as shown in the Figure. Often pieces of this surface resemble an exaggerated washboard.

The next category is used for aa-lava in place: This is the form that has not been broken from the body of the flow by its internal movement, or by other causes. Very good examples of such lavas have been noted on the Hawaiian lava-fields both near Kilauea Volcano and in Kona, and in the Modoc Lavas at the end of the Devils Homestead Lava Field in northern California. The measure of roughness here was easily a meter, or a yard, in some selected places.

Aa-rubble and clinker is next and is composed of loose broken fragments of aa; it is scoriatious in appearance though of different origin than scoria. It has largely formed on the surface of the lava, not in the throat of the vent under the impulse of a pyro-explosion. For that reason the writer does not believe that it should be called scoria, but rather rubble or clinker. The size of these fragments is variable, though some portions of a lava-field may be composed of such

fragments all of one order of size. Some gradation is needed similar to pebble, cobble, and boulder. It is suggested here that clinker may do for the larger fragments (larger than six inches across) while rubble may easily fit the smaller fragments, for the smaller kinds do not clink, but grate and rattle when shifted.

In the bottom-right corner of Table 1 is placed block-lavas. Here again some approximate division is needed for the different sizes of blocks. However, no blocks smaller than about six inches have been noted by the writer. Such a surface is found on the Schonchin Flow for several hundred feet around the Butte of that name in the Modoc Lava Beds. In the same area near the source of the Black Lava Flqw, on the south slope of Cinder Butte, there are some blocks as large as small houses (10 to 20 feet on different edges). As far as general appearance goes, a block-lava might well be compared to a talus of blocks, but again they did not form in the fashion of a talus. Though it is not certain in what manner they formed, it is thought that the lavas cracked into blocks under cooling stresses, and they were shifted out of position by the movements of the underlying mobile lava.

Boulder City, Nevada

AMERICAN GEOPHYSICAL UNION

TWENTY-FOURTH ANNUAL MEETING

SECTION OF TECTONOPHYSICS

REPORTS AND PAPERS

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FLOWAGE AND RECRYSTALLIZATION IN PALEOZOIC QUARTZITES

Robert E. Fellows

(Abstract)

The lower limit of visible traces of penetrative movement in quartz-rich rocks can be defined by studies of orientations and mutual relations of grains. Intensity of deformation in the central Appalachians decreases gradually from the crystalline Piedmont toward the north, northwest, and west perpendicular to the regional trend. The author has attempted to determine the limits of visible deformation geographically and stratigraphically.

Five types of quartz have been distinguished on the basis of texture: Original grains, peripheral growth quartz, crush quartz, needle quartz, and recrystallized quartz. Each type indicates a particular degree of deformation grading from original grains showing little or no deformation to completely reoriented and recrystallized SiO_2.

If granulation affects 22 per cent of the quartz present, a lineation may become visible megascopically. It is then perpendicular to the fold-axis b, contained within the flow-cleavage plane, and parallel to a. Arrangement of grains into physical parallelism precedes the development of preferred optical orientations. Lattice parallelism develops either through fracturing or through coalescence of reorganized crushed-quartz particles.

A study of the regional distribution of recrystallization and flowage on a quantitative basis permits the definition of a transitional zone in which the nontectonites on the northwest merge with the tectonites on the southeast. Fabrics of rocks in the tectonite area are readily deciphered, while those northwest of the demarcation-belt are increasingly indistinct.

[The complete paper will be published in the Bulletin of the Geological Society of America.]

U. S. Geological Survey,
Washington, D. C.

PETROGRAPHY AND FABRIC OF GNEISS DOMES NEAR BALTIMORE

Karl Stefansson

No abstract or manuscript of this paper was submitted.

U. S. Geological Survey,
Washington, D. C

FABRIC CHANGES INDUCED BY EXPERIMENTAL DEFORMATION OF MARBLE

Eleanora Bliss Knopf

The correct interpretation of petrofabric data has been waiting for many years for assistance from the study of experimentally deformed rock-fabrics. The rock-deformation at high confining pressures, carried on by David T. Griggs at Harvard University, was an ideal field for such a study and it was agreed to carry out a series of carefully controlled experiments upon definitely oriented rock-cylinders, whose original fabric had been determined by petrofabric analysis and whose deformed fabric would be studied in the same way.

Marble from the Yule marble quarry of the Vermont Marble Company, in Colorado, was selected for the investigation because marble had proved well suited for experimental work. Unfortunately, it proved impossible to obtain a statistically isotropic rock for the work, but the Yule marble is a pure, mono-mineral calcite aggregate, of grain-size that can be studied satisfactorily with the universal stage, and has a fabric which, although anisotropic, is reasonably simple, so that the influence of the anisotropy upon the course of deformation can be estimated and recognized.

Petrofabric analysis demonstrated that the internal space-arrangement of the calcite-grains emphasizes and confirms a dimensional preferred orientation which, although inconspicuous, can be recognized by a careful megascopic examination. The dimensional preferred orientation is in an almost vertical plane, striking within a few degrees of north. The grains are flattened and ellipsoidal, almost discoidal, in shape, with the shortest axis of the ellipsoid in an approximately east-west direction.

The poles of crystallographic planes corresponding to the e-planes of calcite, that is, the negative flat rhombohedron $\{01\bar{1}2\}$, are concentrated in the east-west direction, showing that the gliding planes of calcite lie mainly in the megascopic slip-plane of the fabric that is indicated by the dimensional preferred orientation of the grains. This suggests that the mechanism by which these grains have acquired their preferred orientation was a flattening accomplished by gliding along the flat rhombohedral planes. The optic-axis maximum in the Yule marble lies in the horizontal plane about 26° from the main maximum of the calcite glide lamellae.

Three sets of test-cylinders were cut in such a way that the axes of one set are normal to the megascopic slip-plane; the axes of the other two sets lie in the megascopic slip-plane, one set with axes parallel to the strike, the other set with axes parallel to the dip. The accurate turning and cutting of these oriented cylinders is an expensive operation; and it is a pleasure to me to acknowledge here, with deep thanks, a grant from the Marsh Fund of the National Academy of Sciences to defray the cost of preparation.

Five experiments in compression were carried out on these cylinders by Mr. Griggs. Confining pressures ranged from 10,000 to 12,500 atmospheres. Two sets of cylinders with axes normal to the megascopic slip-plane and parallel to the dip of the megascopic slip-plane were deformed dry at room temperature. One set with axes parallel to the strike of the megascopic slip-plane were deformed dry at 150°C and another set with the same orientation were deformed at 150°C in the presence of H_2O and CO_2. The permanent deformation attained in these experiments ranged from 20 to 30 per cent in the dry deformation to 40.6 per cent in the wet deformation. All the cylinders came out of the press intact and were sent to be thin-sectioned in three directions, respectively parallel to the strike and to the dip of the slip-plane of the undeformed fabric and normal thereto. Unfortunately the cylinder whose axis was normal to the slip-plane of the undeformed fabric disintegrated before it could be thin-sectioned. It was planned to repeat this experiment, but the exigencies of war have put a stop to the experimental work for the duration.

The cylinder, whose axis was normal to the original slip-plane of the fabric, showed a circular cross-section after deformation. The other two cylinders, with axes in the original slip-plane, became elliptical in cross-section with the major axis of the ellipse in the east-west direction in both cylinders, an orientation that is predetermined by the position of the axes maximum in the undeformed fabric. The axes lie approximately east-west. The gliding direction in the glide-plane of calcite is parallel to the trace of the optic axis. Hence the predominant displacement of material must be in the east-west direction regardless of how the force is applied, provided that the deformation takes place by intragranular gliding.

Petrofabric analysis of the sections cut from cylinders whose axes are parallel respectively to the strike and dip of the original slip-plane, shows the striking result that the dimensional preferred orientation has swung through 90°, so that the flattened grains in the new fabric occupy planes that are transverse to the direction of compressive force. This swing in dimensional preferred orientation is accompanied by a complete swing of the fabric axes, so that the (ab)-plane in the new fabric comes to lie, in general, transverse to the axis of compressive force. The lamellae or the axes maxima in all the petrofabric diagrams, both in the undeformed and the deformed fabric, are double maxima lying in two planes that intersect along the b-axis of the fabric at such a low angle that these two intersecting planes approximate very closely the position of the (ab)-plane established by the dimensional preferred orientation.

This structure was recognized by Sander as characterizing a certain type of tectonite fabric in metamorphosed rocks. He interpreted this fabric as the result of a flattening mechanism and it is an important result of the experimental work that the fabric-analysis from rocks actually compressed in the laboratory confirms the interpretation of similar fabrics in metamorphosed rocks as the outcome of a flattening process accomplished by grain-gliding. The second important result of this experimental work is the confirmation of the idea that calcite deformation takes place largely by gliding of calcite along $\{01\bar{1}2\}$ in the direction of [0001], and that the direction of movement in a deformed rock can be recognized by the relation between the optic axes and the lamellae maxima.

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METHOD OF MEASURING CHANGES OF STRATIGRAPHIC THICKNESSES DUE TO FLOWAGE AND FOLDING

Ernst Cloos

In two previous papers, the author has called attention to the possibility of measuring rock-flowage quantitatively [see 1 and 2 of "References" at end of paper]. Inasmuch as a complete report on the method and its application is delayed due to the emergency, the author feels justified in presenting a brief outline at this time. Oolite deformation in the central Appalachians has been measured systematically under a grant from the Penrose Bequest of the Geological Society of America and a comprehensive report on that work will be published later.

Introduction--Folding without visible fracturing has long been a perplexing problem. At depths under the influence of pressure, heat, magmatic injections and solutions, plastic distortion may be explainable, but near the surface, bending of consolidated sandstones, limestones, or even shales into elegantly curved folds seems mechanically impossible. If the Paleozoic sequence of the Appalachian Geosyncline were folded near the base and fractured near the top, depth of burial and load may be related to plasticity or brittleness of the whole complex or its members. The uppermost formations like the Pottsville Sandstone, however, are as much and as smoothly folded as the Cambrian quartzites and accompanied with as little fracturing. Joints are common but transect folds.

Externally, the folds are similar; internally, they differ considerably. From top to bottom of the section, metamorphism increases, crystalline constituents are rearranged, cleavage appears, and evidence of flowage is strong in the lower portions of the section. Increasing intensity of deformation downward is paralleled by lateral increase from northwest to southeast either because older formations appear below younger ones in the same direction or because metamorphism increases approaching the igneous or crystalline axis of the Appalachian Orogen [3]. It is not clear whether the increase of deformation-intensity is a function of depth, of age, or of distance from the crystalline axis. Since the same formation, as for instance the Antietam schist, grades from a sandstone into a garnetiferous mica-schist as one proceeds southeastward, variation of intensity of deformation may well be related to all three factors in various degrees.

The Appalachian Orogen can be divided into longitudinal belts on the basis of deformation-intensity, texture, cleavage, crystallinity, or a combination of these factors. In an outer zone, all rocks are thrown into folds and jointed but without recrystallization and penetrative movement [4]. The rocks are non-tectonites. Parallel to this zone and southeast of it is a tectonite belt in which deformation is accompanied by recrystallization, and cleavage follows a regional trend and a uniform dip. From here on southeastward, metamorphism increases gradually and several metamorphic zones have been suggested by Hietanen [5]. In the "inner" zones, recrystallization is complete, fossil evidence is destroyed, and correlation problems dominate [5] the investigation.

Bailey Willis in 1893 [6] divided the Appalachian Province into four districts on the basis of prevailing structural types: Open folding; close folding; folding and faulting; and folding with schistosity. Recently Fellows [7] has shown that the boundary between the non-tectonite and tectonite zone can be determined on the basis of quartz-deformation.

Folding, recrystallization, formation of cleavage, and any rearrangement of constituents without rupture take place either in unconsolidated or little consolidated rocks or in a plastic state. In other words, the Pottsville sandstone was either not a sandstone prior to its folding, or it was buried deeply. Inasmuch as we know of no rock-column, thick enough above the sandstone, the author believes that the sandstone was only partly or poorly consolidated and that consolidation is to a large part due to folding. If unconsolidated rocks like sand, clay, and others are "folded", the individual constituents are free to move without severe deformation. In consolidated rocks or under pressure, the individual grains may be deformed, cleaved, aligned, and distorted because the grains are set in the matrix without freedom of movement. A load of gravel can well be dumped without damage to the pebbles. A block of concrete, however, will be broken and many of the fractures transect matrix and pebbles alike.

It may well be that the boundary between tectonites and non-tectonites as established by Fellows [7] is the transition-zone between a "higher" region in which quartz-grains were free to move in a matrix and a "lower" one in which they could not move. In addition, movements have probable become more intense and penetrative with depth.

It seems rather obvious that folding in all its modifications is accomplished by flowage, that

is, by irreversible deformation beyond the elastic limit and below the rupture-point.

Flowage is difficult to determine quantitatively and small amounts will most likely evade observation. Thickening of anticlinal crests and thinning of limbs of folds have frequently been observed but rarely can they be evaluated quantitatively. Distortion of fossils, pebbles, amygdules, oolites, and other known shapes have been mentioned. The most outstanding analysis of distorted fossils is by Albert Heim [8] who described elongated belemnites and oolites in relation to orientation of flow-cleavage. Unfortunately, his work is much too rarely referred to.

Zonal arrangement of deformation in the Appalachian Province and increasing intensity southeastward is accompanied by varying amounts of rock-flowage which in turn must mean varying amounts of distortion of stratigraphic thicknesses.

The thickness of a bed is a function of the amount of sediment deposited primarily and later alterations. These may consist, for instance, of compaction, dehydration, recrystallization, or flowage. If the flowage-direction is at an angle of more than 45° to the bedding-planes, thickening is likely; if the angle is less than 45°, the beds may have thinned.

Stratigraphic thicknesses are usually measured with great care and then accepted as representative. Variations are as a rule taken to mean differences in depositional thickness. Many such sections have been recorded without reference to large or small structures, to the portion of a fold in which it is located, or to the position of cleavage with respect to bedding-planes.

In the author's opinion, measurements of stratigraphic thicknesses remain more guesses without most careful structural analyses of the processes that may have distorted the section. Such analysis should include not only obvious faulting but also distortion by flowage. Furthermore, the measured section should be located with respect to the above-mentioned zones. The amount of mineral rearrangement or recrystallization will furnish an index to the reliability of measurements and cleavage will furnish a clue to the direction and intensity of flowage.

The author is aware of the fact that stratigraphic thicknesses vary, but it seems a strange coincidence that they always seem to grow thicker with increasing intensity of deformation!

Recognition of flowage--Recognition of flowage is difficult in the absence of distinct flowage-structures. Flowage prior to consolidation will scarcely leave other traces but the distortion of a bedding-plane or the apparent bending of a pre-existing design. In more advanced stages flowage-structures may be preserved as parallelism of minerals or elongation of bodies of known shapes like oolites or pebbles.

Flow-cleavage [9] becomes visible only after a minimum of deformation is reached and mineral rearrangement has taken place. If this limit is exceeded, the cleavage becomes increasingly "strong", more and more conspicuous, and in the higher stages of metamorphism, bedding may be obliterated entirely. As can easily be shown from measurements of oolites and other known shapes, the cleavage-plane is a flowage-plane and includes the maximum and mean direction of extension (flowage).

If direct observation and determination of the flowage-direction is impossible, cleavage may furnish at least the direction of extension or reduction of a section and the angle between cleavage and bedding will indicate whether a section is thickened or thinned.

In spite of their importance, the author knows of only few type-sections in which attitude and intensity of cleavage, bedding, fold-axes, and lineations have been recorded.

If it were possible to measure distortions of thicknesses at every point of a section, correlations would become increasingly reliable, and depths of basins of sedimentation could be determined. In addition, such determinations may permit reconstructions of folded terranes.

Determination of flowage-directions, cleavages, lineations, and other structures is relatively easy either in the field or microscopically. Quantitative determinations, however, are more difficult but very promising.

The method--In order to analyze deformation, it has become customary to consider the changes of a theoretical sphere and to use three coordinates as axes of maximum, minimum, and mean distortion. Such spheres do not, as a rule, occur in rocks and the position of the axes has to be determined in some indirect way or remains conjectural.

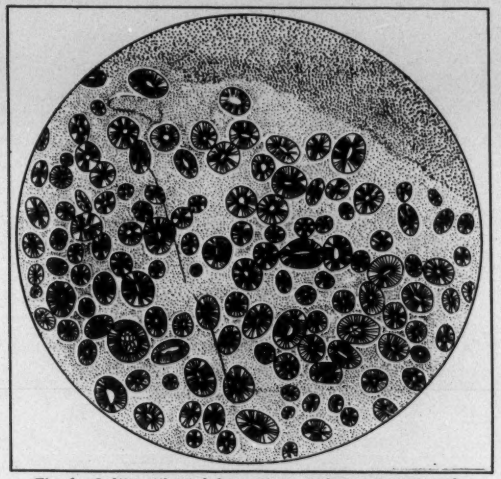


Fig. 1--Oolite without deformation; random orientation of elongated shapes is rather typical (Contact Rochester and McKenzie formations, Tyrone Quadr., Pennsylvania)

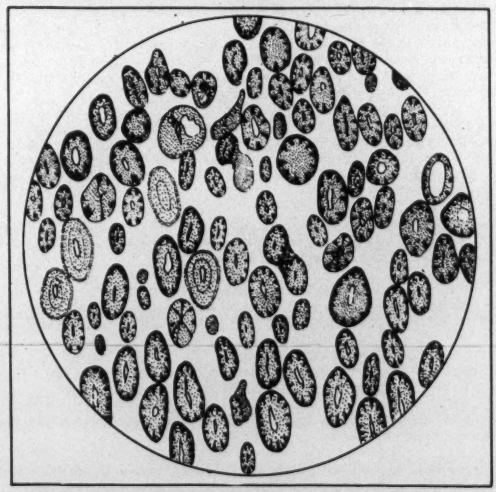


Fig. 2--Oolite deformation 24 per cent; in spite of varying sizes, ratio of each ooid is similar to all others (Cambro-ordovician Hagerstown Quadr., Maryland)

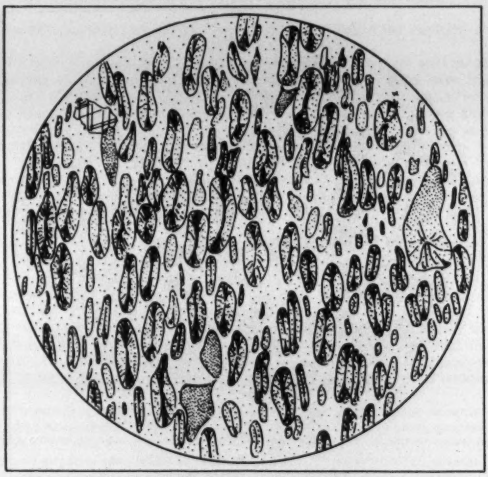


Fig. 3--Deformation 50 per cent (Conococheague limestone north of Sharpsburg, Maryland)

The most perfect natural sphere with wide geologic distribution is the ooid in oolitic limestones. In spite of the vertical restriction of oolites in the stratigraphic sequence to only a few formations, they are quite persistent laterally. The most serious objection to the use of oolites as indicators of deformation is the fact that the physical properties of limestones are not the same as those of sandstones and shales of the same section. But if directions and deformation-axes are once established within an oolitic series, they can be traced into overlying and underlying formations with the help of distorted fossils like crinoids and others.

The author has used oolites in a systematic investigation of the central Appalachians between the Susquehanna and Potomac Rivers in Pennsylvania and Maryland and it has been possible to determine zones of equal intensity of deformation, to establish the directions of maximum elongation at several hundred localities, and to suggest corrections for stratigraphic thicknesses as established in earlier reports [2].

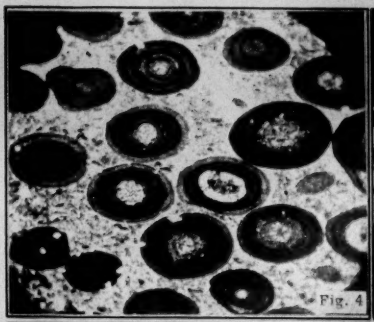
Figures 1 to 9 show nine sections through oolitic limestones in the order of increasing intensity of deformation. Figures 1 to 3 are camera-lucida drawings and the others photomicrographs. The average size of the ooids is between one-half and one mm.

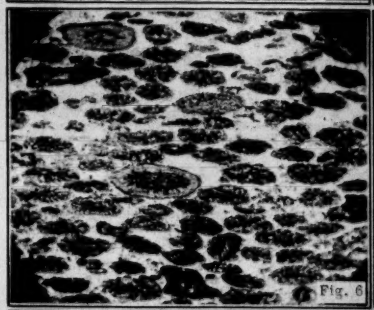
Figure 1 is a "hard" oolite with dolomitic ooids and fine crystalline calcite-matrix. The deformation is so slight that statistical measurements of over 50 individual ooids provide no uniform orientation. Each grain is surrounded by a very thin coating of clear, recrystallized calcite.

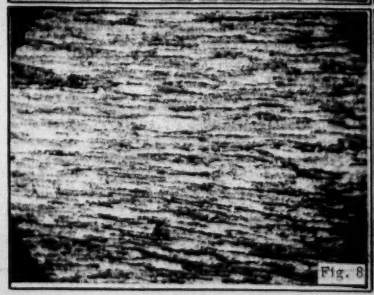
Figure 2 shows a uniform orientation of all components. Several kinds of ooids participate and even the larger ones are slightly flattened. Statistical measurements show a very distinct orientation and an extension of 24 per cent of the diameter of the unit-sphere.

In Figure 3 large and small ooids are much elongated. Small mud lumps take part in the orientation; extension is 50 per cent of the unit-sphere.

The photomicrographs, Figures 4 to 8, show the gradual increase of the extension of the major axis of deformation. In spite of the difference between the oolite composition, color, and shape, the orientation is already established when deformation reaches 15 per cent. From here on upward only intensity increases; orientation remains fixed. In Figure 8 measurements are no more







Figs. 4-9--Microphotographs

(4) Oolite in upper Conococheague limestone (Potomac River section; deformation 23 per cent)
(5) Oolite in lower Beekmantown limestone (Hagerstown Quadr., Maryland; deformation 52 per cent)
(6) Dolomitic oolite, Conococheague limestone (Dickinson, Newville Quadr., Pennsylvania; deformation 68 per cent)
(7) Strongly elongated oolite; ends of ooids partly drawn out and lost (Emmertsville, Hagerstown Quadr., Maryland; deformation 140 per cent, minimum value)
(8) Extreme deformation of over 220 per cent; ooids can still be recognized but not measured (Conococheague limestone 3 miles north of Mt. Holly Springs, Carlisle Quadr., Pennsylvania)
(9) Elongation of ooids at angle of 75° with bedding plane as indicated by boundary between finer grained material and oolite [Cut normal to fold-axis ('b'), maximum elongation in 'a']

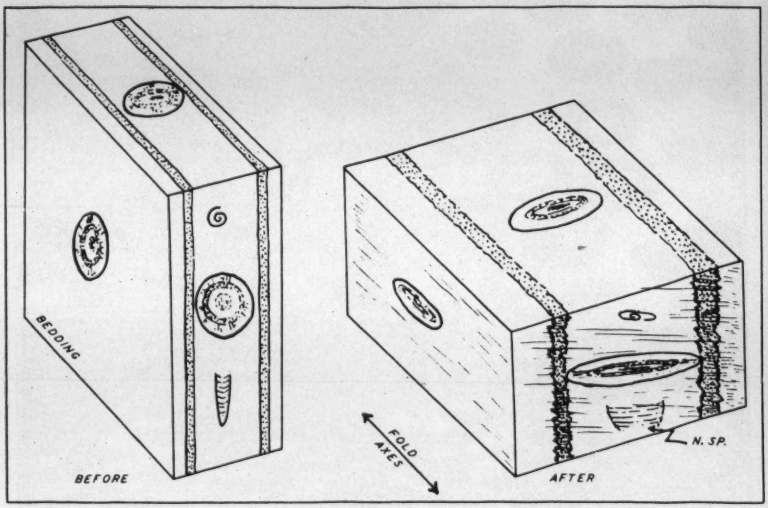


Fig. 10--Diagrammatic presentation of deformation of oolites at large angle to bedding (Distance between bedding planes increases as elongation in 'a' takes place and axial plane cleavage forms; constructed for ratio of a/c = 4/1; Emmertsville, Hagerstown Quadr., Pennsylvania)

possible but the oolitic character is still evident. Oolites of the type of Figures 7 and 8 are not recognizable as such in the field because of the obliteration of textures but a strong lineation in the cleavage-planes (in "a") becomes visible megascopically.

Figure 9 shows a bedding-plane with fine-grained limestone on one side and oolite on the other. The plane itself is wrinkled because of the reduction of the vertical and increase of the lateral distance.

Undeformed oolites can be assumed to be spherical if some care is taken to eliminate primarily elongated shapes, twins, or freaks. Even if an occasional odd-shaped ooid is measured, its orientation would be accidental and disk-shaped ones would parallel bedding. Measurements of large numbers of irregularly shaped ooids show no preferred orientation (Fig. 1).

If deformation has been sufficiently intense, the ooids assume an elongate shape and the three axes of deformation can be readily determined (Figs. 2-9).

Most oolites are rather small and the average size is below 1/2 mm. Microscopic measurements are, therefore, essential and accurate determinations are possible only in thin section and by measuring at least 35- to 50-ooid dimensions and computing the average.

Specimens are oriented in the field and the orientation is preserved throughout the analysis. This is necessary where orientations are plotted into maps and correlated with orientations of cleavages and lineations as measured in the field.

Recognition of oolites is a matter of practice and is very much easier on weathered surfaces than on fresh ones. All possible structure elements should be measured and cleavages, lineations, fractures, bedding, and fold-axes should be known from every locality and, if possible, from several measurements in the vicinity.

Most important is the determination of the proper saw-cuts. Deformed ooids are studied

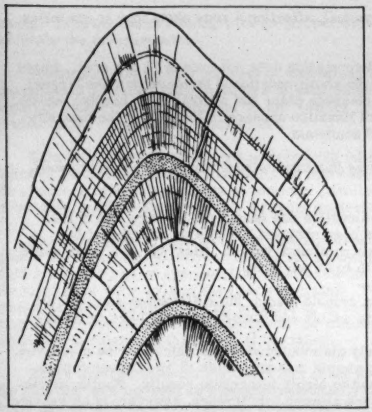


Fig. 11--Fold showing thickening in crest and transecting cleavage (Within shaly beds maximum elongation is in 'a' normal to fold-axis; Juniata River section)

under a binocular and with a hand lens. The principal axes of deformation, however, become apparent only in three-dimensional analysis. In taking specimen in the field it is, therefore, essential to secure three mutually perpendicular surfaces if at all possible. Inasmuch as there is nothing in a thin section to indicate whether an ooid is cut along its largest axis or at 20° or 30° from it, several sections may become essential.

The author has cut two mutually perpendicular sections in every case and in 20 per cent of all cases a third one. If two sections are then measured, one axis is determined twice and supplies a very desirable check on the other two.

Where deformation is very intense the ends of the ooids are pulled out and possibly lost. Measurements of such axes are then too small and computations become minimum values. Figure 7 shows such elongated ooids where the ends are difficult to determine accurately and it represents the limiting value.

Assuming constant volume, the computation of the original average diameter of an ooid is simple according to the following formula:

$$(4/3)\ \pi r^3 = (4/3)\ \pi a \times b \times c$$

$$r = \sqrt[3]{a \times b \times c}$$

a, b, and c are the measured half-axes of the ooid as measured in two mutually perpendicular cuts and r is the radius of the unit-sphere. If, for instance, the measured values are 2a = maximum diameter = 8.45, a = 4.23, 2b = mean diameter = 6.74, b = 3.37, 2c = minimum diameter = 5.06, c = 2.53, then $r = \sqrt[3]{4.23 \times 3.37 \times 2.53} = 3.3$ and d = 6.6.

The components of deformation are, therefore, 2a = +1.85; 2b = +0.14; 2c = -1.54.

In reference to the original sphere the maximum extension in "a" is (1.85 × 100)/6.60 = 28 per cent.

If the mean axis is assumed to remain constant, the value is less accurate but a simplified two-dimensional calculation can be used if only one cut is available.

In order to simplify procedure the author has used the same coordinates as accepted by fabric students [4, 10]: b is the direction of the fold-axes; a is perpendicular to b and is the direction of tectonic transport; and c is normal to the ab-plane.

The three ellipsoid axes are then geographically oriented and can be correlated with the fabric coordinates. a is therefore not always the direction of maximum elongation but can under certain circumstances be smaller than b. The ab-plane always parallels or contains the flow-cleavage plane.

Application--The measurement of oolite orientation and deformation is relatively easy. If the oolite layer is persistent or if several horizons are available, the direction and amount of distortion can be determined over a large area. The author has measured deformation at several hundred points between the Susquehanna and Potomac rivers in Cambro-Ordovician limestones, and maps have been constructed showing lines of equal percentage of deformation and of equal ratio (a/c). A "gradient" map shows the strike, plunge, and intensity of extension in a. The boundary between tectonites and non-tectonites is very sharply marked and the increase of

intensity of deformation toward South Mountain is gradual, affecting a zone about four to six miles wide.

Cleavage is not megascopically visible where deformation does not exceed 15 per cent. Above 20 to 25 per cent cleavage grows more distinct. In the above-mentioned tectonite belt the largest extension of all oolites is in the steepest dip of the cleavage plane and normal to b; in other words, in a. If the extension exceeds 50 per cent, a distinct lineation appears in the field. The intensity grows from Hagerstown Valley towards the east and southeast.

Where a is at a large angle to bedding, thickening has taken place; where the angle is small, the beds have thinned.

In determining a it is possible to measure the direction and quantity of flowage and in the South Mountain area values of 200-300 per cent have been obtained. Where oolites cannot be measured, cleavage may be used as a means to obtain minimum values. Cleavage at a large angle to bedding means exaggerated thickness of at least 15 to 25 per cent.

In shales, sandstones, and limestones containing crinoid stems, their distortion may well be used quantitatively. Amygdules in volcanic rocks are usable and distorted pebbles are well known.

Oolites are probably the most common and widely distributed element which may be measured. Whatever means may be used under given condition, simple measurements of stratigraphic thicknesses without careful study of rock-flowage may lead to highly inaccurate results. Faults, unconformities, and thrusts are relatively easily noticed and allowed for; flowage, however, is an evasive factor and grows more dangerous because it cannot be recognized unless it is very pertinent. It is, therefore, mostly unrecognized and neglected. It seems almost futile to measure sections in inches if flowage may have increased or decreased thicknesses by amounts of feet or hundreds of feet.

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ORIENTATION OF ILMENITE AND ANDESINE FROM THE ST. URBAIN, QUEBEC, TITANIFEROUS IRON-ORE DEPOSIT

O. F. Tuttle

(Abstract)

As there has been no satisfactory method developed to measure and record the orientation of the opaque ore-minerals, a technique is proposed whereby the orientation of many of the opaque minerals can be measured and statistically recorded on the conventional contoured petrofabric diagram.

The method is limited to minerals that have a planar element related to a crystallographic direction that will permit measurement and subsequent recording of the orientation of that crystallographic direction. Some planar elements that can be readily used are: Cleavage; twinning; exsolution plates, when they exhibit relatively sharp boundaries and uniform orientation; crystal faces; replacement or alteration along crystallographic directions; and compositional banding or

zoning. In many cases etching with the proper solvent will bring out these structures and greatly facilitate the measurements.

Essentially the method consists of measuring the "dip" and "strike" of the planar element on two polished surfaces at right-angles to each other (with, of course, a correction for the "dip" when not measured perpendicular to the "strike"). The pole to the planar element can then be plotted on the conventional Schmidt net.

This technique has been used in preparing fabric diagrams of the ilmenite from the St. Urbain, Quebec, titaniferous iron-ore deposit. In this case the measurements were greatly facilitated by the presence of exsolved plates of hematite parallel to (0001) of the ilmenite. Subsequent plotting of the pole to these plates gives a diagram equivalent to a c-axis diagram of ilmenite.

The most unusual feature of the ilmenite orientation is the lack of symmetry in the fabric diagram. A megascopic s-surface is denoted by the alignment of the somewhat platy ilmenite grains. This s-surface has no symmetrical relation to the statistical or lattice s-surface brought out by the plotting of the c-axis of the ilmenite grains. The degree of preferred orientation of the ilmenite is surprisingly high with maxima up to 12 per cent of the grains in a one per cent area. This lack of symmetrical coincidence of the dimensional and crystallographic orientations undoubtedly is related to the origin of the fabric.

There are two theories for the origin of the St. Urbain ilmenite deposit, one theory being that the ilmenite was injected as a magma essentially of ilmenite composition, hence making the fabric depositional in origin. The second theory ascribes their origin to a replacement-process, making the fabric the result of volume for volume replacement of the enclosing anorthosite. The mechanism of imparting such a high degree of preferred orientation to a mineral by metasomatic processes deserves more study and may have wider application in the more common rocks as well as in ore-deposits.

Fabric diagrams of the andesine of the enclosing anorthosite were prepared. The preferred orientation is not so pronounced [c-axis diagram maxima, 3.5 per cent; (010) diagram maxima, 6 per cent] as that of the ilmenite, and here again there is no symmetrical relation between the statistical s-surfaces indicated by the (010) or the c-axes of the andesine and the megascopic or the statistical s-surfaces in the ilmenite.

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PLASTIC BASINING OF THE PACIFIC AND ITS RELATION TO GLACIATION AND SUBMARINE CANYONS

H. T. Stearns

No abstract or manuscript of this paper, which was presented by title, was submitted.

U. S. Geological Survey,
Washington, D. C.

VARIATIONS IN PHYSICAL PROPERTIES WITHIN THE EARTH'S CRUSTAL LAYERS

Beno Gutenberg

(Abstract)

An investigation of amplitudes of $\bar{P}$-waves in southern California in about 300 instances, having epicentral distances from 50 to 570 km, indicates that the velocity V of longitudinal waves in the granitic layer at depths h (in km) between about 2 km and its bottom at about 18 km is given by $V = (5.56 + 0.001\ h)$ in km/sec. The second term is a first approximation only and indicates an increase in the bulk-modulus by about 3/4 per cent corresponding to an increase in pressure by 1000 atmospheres. This is of the same order of magnitude as the values found for granite in laboratory experiments and from the theory of finite strain.

Similarly, the investigation of Py-waves gives a velocity of [6.0 + 0.01 (h-18)] in km/sec for the (first) intermediate layer and a resulting increase in the bulk-modulus by about 1-1/4 per cent per pressure increase of 1000 atmospheres. Travel-times as well as amplitudes lead independently to the conclusion that most of the 50 shocks used originated at the bottom of the granitic layer. In shocks with faulting completely inside the granitic layer only, the amplitudes of Py should be about the same size as those of Pn.

The fact that the amplitudes of the various S-waves change with distance in a similar way as those of the corresponding P-waves, indicates that the effect of pressure and temperature on the coefficient of rigidity is relatively the same as on the bulk-modulus.

The Mohorovičić discontinuity is at a depth of about 35 to 40 km in the coastal areas of southern California, but deeper under mountain ranges. The velocity of Pn below it is close to 8.0 km/sec. At first, the velocities of both, P and S, increase with depth, probably at a rate similar to that in the upper layers, but the rate of increase falls off rapidly with increasing depth, resulting in a rapid decrease of the amplitudes of Pn and Sn with distance beyond Δ = 200 km. Amplitudes of Pn and similarly of Sn in intermediate shocks without appreciable surface-waves, on records of shocks originating at various depths within a radius of about 2000 km from Huancayo, Peru, and recorded at the station there, confirm the previous results of Gutenberg and Richter concerning the relationship between the epicentral distances at which the amplitudes of Pn are very small, and the focal depth of the shocks. These findings can be explained on the assumption that at a depth of about 80 km the melting-point of the material is reached. Immediately above that critical depth, the effect of temperature on the bulk-modulus and on the coefficient of rigidity may approach, or even surpass, the effect of pressure. At the critical depth itself, there may be a slight sudden decrease of the wave-velocity. At greater depth, the effect of the temperature on the bulk-modulus and the coefficient of rigidity becomes more and more insignificant. Whereas above the critical depth a certain minimum stress, the strength, is required to start plastic flow, below this depth no appreciable strength exists, and the plastic flow is controlled only by the viscosity of the material.

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AMERICAN GEOPHYSICAL UNION

TWENTY-FOURTH ANNUAL MEETING

MINUTES GENERAL ASSEMBLIES

AND SECTIONS

Washington, D. C.
April 23 and 24, 1943

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TWENTY-FOURTH ANNUAL MEETING (1943)
MINUTES, GENERAL ASSEMBLIES AND SECTIONS

BUSINESS SESSION

The Business Session of the General Assembly of the American Geophysical Union was held at 12:15 o'clock on Saturday, April 24, 1943, in Room 101 of the Hall of Government of George Washington University, Washington, D. C. The Session was called to order by Vice-President L. H. Adams with a registered attendance of some 60 members [see Appendix A for complete registration].

The minutes of the General Assembly of the Twenty-Third Annual Meeting on April 3, 1942, published in the Transactions of 1942 and distributed to all members, were approved as printed.

The annual report of the General Secretary [see Appendix B] was summarized briefly, accepted with thanks, and ordered printed in full in the Transactions of 1943.

Reports of Standing Committees

Chairman Musgrave's report of the Committee on Membership is printed in full in Appendix C.

The report of the Committee on Statutes and By-Laws, presented by Chairman Harradon, is given in Appendix D.

In the absence of Chairman Swick on account of illness, Dr. Fleming reported that the Budget Committee had submitted a budget on September 4, 1942, for the fiscal year July 1, 1942, to June 30, 1943, which was accepted by the Executive Committee [see Appendix E]. It included expected receipts of $12,500 (including balance on hand July 1, 1942), authorized expenditures of about $7,900, and indicated an estimated balance of $4,600 as a reserve for contingencies and possible change in form of the Union's Transactions to the proposed bimonthly American Journal of Geophysics if that becomes practicable.

Chairman Marble of the Committee on Meetings summarized his report [see Appendix F] by stating that the work of the Committee speaks for itself through the sessions of the Twenty-Fourth Annual Meeting. He thanked all the Secretaries and Presidents of Sections for their part in making the meetings successful.

Chairman Fleming of the Editorial and Publication Committee had no formal report to make but preferred to let the Transactions of 1942 speak for themselves.

Reports of Special Committees

The report of Chairman Disney for the Special Committee on Cooperation with International Commission for Study of Tidal Waves is given in Appendix G. He recommended that the Committee be discharged in view of the present international situation. Following discussion a motion to discharge the Committee was not accepted because it was deemed desirable that the Committee continue its functions, as far as conditions permit, and so maintain continuity pending full resumption of the International Union's activities after the war.

In the absence of Chairman Hess of the Special Committee on Geophysical and Geological Study of Oceanic Basins, Dr. Thom stated that, because of relations to war developments, a written report must be postponed. He reported that processes are in operation which will make the continuation of the work of the Committee extremely useful when the war emergency is over.

The report of the work of the Special Committee on Geophysical and Geological Study of Continents under the chairmanship of Dr. Thom is given in Appendix H.

Chairman Fleming of the Special Committee on Establishment of American Journal of Geophysics stated he had nothing to report other than what has been said before but that the Committee would make a report [see Appendix M] in the Transactions of 1943 to supplement the report of the Special Committee on Finance. The matter hinges largely upon the obtaining of the necessary funds for a full-time General Secretary and Editor. Good progress is being made in that the Union now has a prospective balance of $4,500 to apply against such an item.

In the absence of Chairman McNish, Dr. Fleming read the report of the Auditing Committee

[Appendix I] which showed that the records of receipts and disbursements for the calendar year 1942 were correct. It was moved, seconded, and passed that this report be accepted and approved.

Chairman McComb read the report of the Special Committee on Time-Signal Service [see Appendix J].

The report of Chairman Stetson for the Special Committee on Cosmic Terrestrial Relationships is given in Appendix K.

Chairman Field of the Special Committee on Finance reported for the Committee [see Appendix L].

An announcement was made that Chairman Colbert of the Special Committee on Award of William Bowie Medal had already submitted a report and that the fifth award of that Medal would be made at the General Assembly to be held shortly after the end of the business session [see pp. 7-8].

The report of the Special Committee on National Welfare and Related Functions was read by Chairman Field [see Appendix N].

It was moved, seconded, and carried that all of the above reports, that had not been acted upon separately, be accepted and filed.

Mr. Howe asked regarding proposed changes in the Statutes and By-Laws pertaining to foreign members, and in reply Chairman Harradon of the Committee indicated certain changes which are to be submitted for approval by the Executive Committee. In reply to a question as to how nominations for Corresponding Members are made, Messrs. Harradon and Musgrave stated that they originate in the Executive Committee.

Unfinished business

The matter of affiliation of snow-survey conferences with the American Geophysical Union was taken up. It was agreed that nothing should be done in this connection since every effort is being made to have persons connected with the snow-survey conferences become members of the Union.

New business

Resolutions--The Committee on Resolutions submitted through Chairman Marble a report [see Appendix O] recommending adoption of nine resolutions which, after discussion, were unanimously adopted as follows:

(1) RESOLUTION OF THANKS TO GEORGE WASHINGTON UNIVERSITY

RESOLVED, That the American Geophysical Union express its heartiest thanks to the authorities of The George Washington University for their kind hospitality in making the facilities of the University available again for the Twenty-Fourth Annual Meeting of the American Geophysical Union on April 23 and 24, 1943, and be it further

RESOLVED, That the General Secretary be requested to thank the University through President Cloyd Heck Marvin for the favors rendered.

(2) RESOLUTION ON MAKING OF PRECISE SURVEYS AND MAPS

WHEREAS, One of the primary purposes for which the American Geophysical Union was established is to promote and coordinate the study of problems concerned with the figure and physics of the Earth, and

WHEREAS, The satisfactory promotion of such a purpose requires the extensive collection and use of information obtained from precise surveys and maps and a knowledge of the technical processes involved in producing and using such surveys and maps, and

WHEREAS, There seems to be a distinct need for the promotion of research in this important field in order that there may result greater economy and coordination of efforts by private and governmental agencies in the making of surveys and maps and in improving the resulting products, therefore be it

RESOLVED, That the American Geophysical Union recommend to the Executive Committee of the Union the appointment of a Special Committee, with members from each Section of the Union, and the assignment to this Committee of the following duties: (a) A survey of technical and scientific procedures in the field of surveying and mapping; (b) promotion of a sustained program of

scientific investigation and research for the improvement of these procedures; (c) an investigation of the possibility of improvement in the coordination of operations by different agencies and in the greater standardization of the resulting products; (d) an inquiry into the surveying and mapping needs of the member sections in planning and executing post-war projects.

(3) RESOLUTION ON CONTINUATION OF ESSENTIAL GEOPHYSICAL OBSERVATIONS FOR DURATION OF WAR

WHEREAS, The demands of war have made it necessary to curtail research not directly essential to war effort, and

WHEREAS, Such curtailment, if carefully planned, can be accomplished with minimum sacrifice of ultimate objectives, and

WHEREAS, An irreparable loss would be that of continuity of records, therefore be it

RESOLVED, That observational programs and services be supported to the extent that all essential geophysical observations be continued for the duration of the war, and that records of the same be properly safeguarded.

(4) RESOLUTION ON IMPLEMENTATION OF METEOROLOGY FOR WAR PURPOSES AND COORDINATION OF CIVIL METEOROLOGICAL FACILITIES OF THE UNITED STATES

WHEREAS, The weather is often a decisive factor in human affairs, both in war and in peace, and

WHEREAS, The science of meteorology can contribute greatly to national efficiency and safety in war and in peace, and

WHEREAS, The basic reseau for observing, recording, reporting, and collecting meteorological facts must be coordinated and unified in order to meet the requirements of synoptic meteorology--a basic function which serves all meteorological interests in common and is distinct from the function of interpretative forecasting for specialized interests, such as the Army and Navy--and

WHEREAS, Accurate and complete meteorological observations and records are of permanent importance for planning and operations, research and development, and other continuing national interests, and

WHEREAS, The general meteorological service of the United States has been vested in the Weather Bureau, therefore be it

RESOLVED, (a) That the American Geophysical Union give full support to the implementation of meteorology for war purposes and to the coordination of the civil meteorological facilities of the United States through the United States Weather Bureau in accordance with Executive Order No. 8991, not only for the war but after; (b) that observations, whether aerological climatological, or synoptic, essential to the basic network be maintained by the Weather Bureau; (c) that observations and records be collected by the Weather Bureau according to a uniform plan so as to be synoptically and climatologically collated and reduced to forms permanently and readily available for utilization by all national interests; (d) that duplication of civil weather observing stations of the basic network be avoided in order that the additional facilities and personnel may be available for war purposes elsewhere; and be it further

RESOLVED, That the Union transmit copies of this Resolution to the Secretaries of Commerce, Navy, and War, and to other interested Governmental and private agencies.

(5) RESOLUTION ON ESTABLISHING MORE STATIONS IN OCEANIC AREA AND ANTARCTICA TO FILL GAPS IN THE INTERESTS OF DAILY AND LONG-RANGE FORECASTING

WHEREAS, There still are large gaps in the observational network over the globe, particularly the oceans and Antarctica, and

WHEREAS, These gaps should be filled in the interests of daily and long-range forecasting as soon as practicable, and

WHEREAS, The establishment of the stations needed would have to be an international proposition, and

WHEREAS, The other geophysical sciences also seek more complete networks of observing stations, therefore be it

RESOLVED, That, when it becomes feasible to establish more stations in the oceanic area and Antarctica, the preliminary plans of the National Weather Service or International Body making them be made known promptly to the Commission on Continental and Oceanic Structure of the International Union of Geodesy and Geophysics, and that the Commission be requested to invite participation of all branches of geophysics in the International Union of Geodesy and Geophysics in the formulation of final plans for each site to be chosen, and be it further

RESOLVED, That copies of this Resolution be sent to the Chief of the United States Weather Bureau, and to the presidents of the International Meteorological Organization and its regional divisions.

(6) RESOLUTION ON TIME-SIGNAL SERVICES BY THE NAVY

WHEREAS, There is a vital need in all seismological investigations for accurate time-service, and

WHEREAS, The added difficulties encountered in maintaining present time-signal services under war conditions are fully recognized, therefore be it

RESOLVED, That the American Geophysical Union again express its appreciation for the radio time-signal services maintained by the United States Naval Observatory, the Naval Communication Service, and the National Bureau of Standards, which time-signal services have been of great aid in all branches of seismology, and be it further

RESOLVED, That copies of this Resolution be sent to the Secretary of the Navy, the Director of the Naval Communication Service, the Superintendent of the United States Naval Observatory, and the Director of the National Bureau of Standards.

(7) RESOLUTION ON ADEQUATE PROGRAM OF SEISMOLOGICAL INVESTIGATIONS IN POST-WAR PERIOD

WHEREAS, The American Geophysical Union recognizes the important opportunities for seismological investigation in the American portion of the circum-Pacific earthquake-belt and the region of the Caribbean, especially in the study of the deeper earthquakes and the measurement of strong Earth-motions, and

WHEREAS, Several countries have, in spite of the difficult conditions, maintained observations and in some cases improved their seismological equipment, therefore be it

RESOLVED, That the American Geophysical Union express the hope that in the post-war period a completely adequate program, including international cooperation in the interpretation of results, be developed, and be it further

RESOLVED, That copies of this Resolution be sent to all of the Governments concerned.

(8) RESOLUTION ON PRACTICAL PROGRAM IN ALL BRANCHES OF GEOPHYSICS FOR POST-WAR PERIOD

WHEREAS, It seems very likely that large numbers of scientific investigators, skilled observers, and technicians will find themselves without employment during the coming period of transision from war-time to peace-time activities, and

WHEREAS, It is quite probable that funds may become available for the execution of special geophysical projects during that period, and

WHEREAS, It seems desirable that plans should be made in anticipation of such funds for geophysical projects of various kinds, therefore be it

RESOLVED, That the American Geophysical Union investigate the feasibility of setting up a practical program which will meet such contingencies in all branches of geophysics.

(9) RESOLUTION ON WAYS AND MEANS OF PROVIDING EMPLOYMENT FOR GEOPHYSICISTS RELEASED FROM WAR EFFORT DURING PERIOD OF TRANSITION FROM WAR TO PEACE

WHEREAS, The need of providing employment for the personnel released from the war effort during the period of transition from a war-time to a peace-time economy is widely recognized, and

WHEREAS, Ways and means of meeting this need are doubtless being considered by constituted agencies, and

WHEREAS, An auxiliary personnel with various degrees of training doubtless can be advantageously employed in many geophysical investigations, in surveys, and in the marshaling of geophysical facts and data (sic), and

WHEREAS, In order to provide such employment at the time when it is most needed, plans and arrangements should be completed beforehand so far as possible, therefore be it

RESOLVED, That the American Geophysical Union appoint a Special Committee, with one or more representatives from each Section of the Union, to undertake the following duties: (a) Make a canvass for suitable projects in geophysics; (b) consider ways and means of realizing the purpose indicated in this Resolution; (c) report findings to the Executive Committee of the American Geophysical Union; (d) make recommendations for further action to the Executive Committee of the American Geophysical Union as soon as possible.

There was discussion of the Committee's report on the present unsatisfactory procedure for handling and presenting resolutions. That procedure makes it necessary to consider, compare, collate, and combine proposed resolutions often within a few hours after submission. It was agreed that the Executive Committee consider promptly ways and means of having all resolutions prepared and distributed in preliminary form before each annual meeting.

Elections--Chairman Musgrave submitted the report [see Appendix P] of the Committee on Nominations nominating J. A. Fleming for reelection as General Secretary of the Union for the

three-year period beginning July 1, 1943. There were no other nominations from the floor, and J. A. Fleming was unanimously reelected with the understanding that the Finance Committee would take steps to provide early relief of the excessive load now carried by him.

The Sections reported the election of the following officers for the three-year period beginning July 1, 1943: Section of Geodesy--J. A. Duerksen as Secretary; Section of Tectonophysics--Ernst Cloos as President, L. L. Nettleton as Vice-President, and M. K. Hubbert as Secretary.

Laboratory of oceanic geonomy--Dr. Fleming read a communication from Dr. T. A. Jaggar with reference to a laboratory of oceanic geonomy, the general purpose of which is sea-bottom geophysics. It was agreed that this communication be turned over to the International Commission on Continental and Oceanic Structure for action.

Earth-Science Institute--Dr. Thom reported on a meeting of a number of representatives of earth-science societies to consider the possible development of an Earth-Science Institute. He stated no formal action was taken but that a committee was appointed to consider whether or not any agency for coordination should be set up and the committee was instructed to prepare final plans to be sent out for consideration by the various societies who sent representatives.

The meeting adjourned at 14 o'clock.

SESSIONS OF SECTIONS

The minutes of the meetings of the Sections of the American Geophysical Union, April 23 and 24, 1943, are given in Appendices Q-a to Q-h.

AFTERNOON GENERAL ASSEMBLY

An account of the General Assembly held in Room 101, Hall of Government, George Washington University, from 14:15 o'clock, April 24, 1943, for the fifth award of the William Bowie Medal, memorials, and conference on the projected program of the International Commission on Continental and Oceanic Structure is given on pages 7-28.

J. A. FLEMING, General Secretary,
American Geophysical Union

APPENDIX A--RECORD OF 475 MEMBERS AND GUESTS WHO REGISTERED ATTENDANCE AT THE GENERAL ASSEMBLY OF THE UNION AND AT SESSIONS OF ITS SECTIONS, TWENTY-FOURTH ANNUAL MEETING, APRIL 23 AND 24, 1943

Adams, L. H.
Adams, Oscar S.
Alkire, H. L.
Allen, Jo Ann
Allen, Roger A.
Anderson, N. G.
Arctowski, Henryk
Arenberg, David L.
Auman, George E.

Bakewell, J. H.
Balsam, Ella
Barrett, Willis C.
Bartsch, Paul
Bates, G. L.
Beard, Charles N.
Benfell, Vincent S.
Bennett, Robert R.
Benscoter, L. K.
Berdan, Jean M.
Bernard, Merrill
Berry, J. W.
Bilzer, Jack
Blake, Archie
Blythe, R. H., Jr.
Bodle, R. R.
Bogan, Willma W.
Bolen, Charles E.
Boos, C. Maynard
Bowie, Mrs. William
Braaten, Norman F.
Brady, James M.
Brancato, G. N.
Brannock, W. W.
Breese, Alexander
Brier, Glenn W.
Brooks, Charles F.
Brotzman, L. E.
Brown, William C., Jr.
Bryan, George S.
Bryant, Jay C.
Bucher, Walter H.
Bunin, Julius
Bunker, Frank F.
Burke, John R.
Burrill, M. F.
Byrd, Mrs. Edna T.

Cady, Wallace M.
Caldwell, Frank E.
Calkins, F. C.
Cameron, D. C.
Capello, Jas. J.
Carlin, Albert V.
Chapman, Robert M.
Choate, H. L.
Claffy, Esther W.
Clapp, Philip F.
Clark, C. O.
Clark, Marjorie O.
Clark, Victor F.
Clifford, Charles J.
Cloos, Ernst
Coffin, L. A.
Colby, Bruce R.
Collins, Elmer B.
Collins, William T.
Concha, Jaime Fernandez
Corcoran, Catherine M.
Cornish, John H.
Cotton, Harold A.
Cowie, Dean B.
Cress, Samuel H.
Crow, Mrs. E. L.
Crowshaw, A. J.
Cunney, George A.
Cunningham, Robert M.
Curtiss, L. F.

Darter, L. J., Jr.
Davenport, R. W.
Davids, Norman
Davidson, Norman
Davies, Frank T.
Davis, Gordon L.
Davis, Grace E.
Davis, Robert M., Jr.
Deel, S. A.
Degani, Meir H.
De Hart, J. R.
De Mallie, Campbell
Demorest, Mrs. Max
Disney, L. P.
Dodge, Homer L.
Dodson, B. E.
Doland, J. J.
Dorney, Margaret
Doutt, J. K.
Dove, W. N.
Drane, Brent S.
Draper, Glen H.
Dryden, Hugh L.
Duerksen, J. A.

Eckhardt, E. A.
Eisenlohr, Wm. S., Jr.
Elford, Carroll A.
Ellingwood, Cecil F.

Farrell, Mary W.
Faust, George T.
Feldman, Cyrus
Fellows, Robert E.
Fiedler, Albert G.
Field, Richard M.
Fish, Charles J.
Fisher, Daniel
Fleharty Mrs. I. D.
Fleischer, Michael
Fleming, Jno. A.
Fletcher, Lyle R.
Flint, Delos E.
Flint, George M., Jr.
Fontaine, Mary Elizabeth
Forbes, Alexander
Forsland, Norma G.
Francis, William A., Jr.
Frey, David G.
Fulks, J. R.

Gallop, Fred A.
Gambrell, J. W.
Garner, Clement L.
Garstens, Martin A.
Gates, George O.
Gault, H. R.
Gebhardt, R. E.
Gehrke, Willis T.
Gensberg, Herbert C.
Gilman, Charles S.
Gish, O. H.
Gish, Pauline
Glass, Jewell J.
Glock, Waldo S.
Goddard, E. N.
Goff, Russell H.
Gold, Harold K.
Goldman, Marcus I.
Goodridge, R. S.
Gottschalk, L. C.
Gottshall, D. N.
Grad, Arthur
Green, J. W.
Greenlee, A. L.
Griffin, Gladys V.
Griffiths, Thomas M.
Grover, N. C.
Grunig, James K.
Grunwell, G. B.
Gumbel, Emil J.
Gunn, Ross
Guthe, Otto E.

Haber, David
Hagen, Norman R.
Hain, E. L.
Halstead, M. H.
Hamilton, Helen C.
Haney, Grace K.
Harradon, H. D.
Harrison, Louis P.
Harrold, John C.
Harrold, Lloyd L.
Harwood, Ernest M., Jr.
Hathaway, Gail A.
Hathcock, Helen W.
Heck, N. H.
Hemple, H. W.
Hendrix, William C.
Hershberger, John

Hersil, Arthur E.
Hertzler, Richard A.
Hess, Frank L.
Hess, Irene
Hester, D. M.
Hewes, Gordon W.
Hildebrand, Pauline L.
Hluchan, S.
Hobbs, Harold W.
Holt, Katherine E.
Holzman, Ben
Hopkins, Charles D.
Hopkins, David Moody
Horn, June
Horner, W. W.
Hough, Floyd W.
Howe, H. H.
Howell, Wallace E.
Hoyt, W. G.
Hubbert, M. King
Hursh, Charles R.
Hyde, Wilma I.
Hyland, Daniel D.

Ingerson, Earl
Izzard, Carl F.

Jacob, C. E.
Jacobs, Woodrow C.
Jarvis, Clarence S.
Jenkins, David S.
Jennings, Arthur H.
Joerg, W. L. G.
Johnson, Charles B.
Johnson, W. G.
Johnston, H. F.
Jones, Benjamin E.
Jones, P. R.
Jones, Stephen B.
Jones, Wm. R.
Jordan, Leland
Joyce, J. W.
Judson, Lewis V.

Kalbfleisch, A. C.
Kennedy, George C.
Keopka, Frances S.
Keulegan, Garbis H.
Keyser, John J.
Killeen, P. L.
Kincer, J. B.
Knapp, David G.
Knoblauch, H. C.
Knoepfel, Margaret F.
Knoll, Denys W.
Knopf, Mrs. Adolph
Kohler, Max O.
Kolb, Eugene E.
Koschmann, A. H.
Krimgold, D. B.
Krumbein, W. C.
Kussman, A. S.
Kutschenreuter, Paul H.

Lackner, Peter R.
Ladd, Robert Boyd
Lager, Ervin J.
Lambert, Walter D.
Lamoreux, Wallace W.
Lamoureux, C. E.
Langbein, W. B.
Lange, Isabelle
Laporte, Lucile
Lay, Edwin T.
Leifson, G.
Lewis, Mrs. Jean S.
Lieberman, H. A.
Light, Phillip
Lindberg, Marie L.
Linehan, Margaret E.
Little, W. S.
Lloyd, J. R.
Ludy, A. K.

MacMillan, Donald B.
Macousky, Morris
Malkin, Louis
Marble, John Putnam
Marmer, H. A.
Martin, Celia S.
Mason, Martin A.
Massey, William S.
Matthes, Francois E.
Max, Andrew J.
McCall, A. G.
McCarthy, Daniel V.
McComb, H. E.
McCombs, Chas.
McCormick, Robert A.
McCracken, E. W.
McDonough, Elven S.
McKay, E. C.
McNish, A. G.
Meadowcroft, Allan J.
Meinzer, O. E.
Meinzer, Mrs. O. E.
Meinzer, Robert, Jr.
Merriam, Carroll F.
Mill, Richard H.
Miller, Don J.
Miller, Suzanne Dewhirsh
Milliken, Donald L.
Mitchell, Hugh C.
Moglen, Norman
Moore, R. Woodward
Moorehead, George S.
Morey, H. F.
Morgan, H. R.
Morrison, R. B.
Mots, Garrett D.
Moxham, Robert M.
Munk, Walter H.
Munns, E. N.
Murata, K. J.
Murphy, Leonard M.
Murphy, Robert Cushman
Murray, James J.
Musgrave, G. W.

Namias, Jerome
Neuberger, Hans
Neumann, Frank
Newlin, Delmas B.
Nordeen, Carl E.
Norris, Clarence
Norton, Anne W.
Norton, Horace W.

O'Connell, Daniel T.
O'Connell, Mrs. Daniel T.
O'Keefe, D. M.
Olmstead, L. B.
Osborn, E. F.
Overholser, James L.

Page, Benjamin L.
Parkhurst, Mrs. Richard
Parkin, Ernest J.
Parkinson, C. P.
Parsons, Willard H.
Patrick, E. C.
Pear, C. B., Jr.
Pearley, Emma
Peavey, R. C.
Peirce, L. B.
Peoples, Joe Webb
Peterson, B. J.
Petterson, Donald R.
Phair, George
Pien, C. L.
Pierce, Charles H.
Poling, Austin C.
Poppescu, Valentina C.
Potter, William D.
Powel, David L.
Price, Reginald C.
Proctor, Patricia
Puffer, Shirley

Ramser, C. E.
Randall, Robert H.
Rappleye, Howard S.
Ratner, Benjamin
Reckord, Gordon E.
Reichelderfer, F. W.
Remmele, Wilbert E.
Revelle, Roger
Rice, Donald A.
Richardson, Robert S.
Ricketts, N. G.
Rigby, Malcolm
Roberts, Kenneth L.
Robinson, G. D.
Robinson, M. A.
Rona, Elizabeth
Rorabaugh, M. I.
Ross, Clarence S.
Rosseland, Svein
Rowe, William M.
Russler, Ben H.

Samuels, L. T.
Sawyer, Donald W.
Sayre, A. Nelson
Schairer, J. F.

Schell, I. I.
Schereschewsky, P. L.
Schick, Charles O.
Schlecht, William G.
Scholl, John C.
Scholl, Mrs. John C.
Schwab, John F.
Scott, Walter E.
Sears, Mary
Seiwell, H. R.
Shalowitz, A. L.
Shapley, Alan H.
Sheridan, Laurence W.
Sherman, K. L.
Sherman, L. K.
Shmidl, Leslie E.
Shneiderov, Anatol James
Shofnos, William
Short, John A.
Showalter, A. K.
Shute, Emil
Siegel, Ethel
Simpson, H. P.
Singewald, Joseph T., Jr.
Skynazi, Helen
Slayton, C. C.
Small, James B.
Smith, Waldo E.
Smith, Wm. O.
Snyder, Franklin F.
Snyder, Janet
Sohon, F. W.
Solet, Ira S.
Sollins, Alfred D.
Solomon, Irving
Soroka, Mary O.
Steele, Rhea B.
Stefansson, Karl
Steiner, W. F.
Stetson, Harlan T.
Steven, Raymond L.
Stevlingson, D. J.
Stewart, Guy R.
Straub, L. G.
Sullivan, Charles L.
Suter, Max
Sutcliffe, Walter D.
Swainson, O. W.
Swenson, Bennett
Swenson, Frank A.
Sykes, Lloyd
Symons, J. M.

Tassi, Gordon J.
Taylor, Geo. H.
Taylor, James H.
Thiessen, Alfred H.
Thom, W. T., Jr.
Thompson, Wilmer L.
Thornthwaite, C. W.
Tigges, Gerald F.
Tonkin, Henry M., Jr.
Tuckerman, L. B.
Turner, Daniel S.
Turner, Howard M.
Turner, Lewis M.
Tuttle, O. F.
Twenhofel, William S.

Urry, Wm. D.

Van Alstine, Ralph E.
Varnes, David J.
Vestine, E. H.
Vhay, John S.

Wahrhaftig, Clyde
Wait, G. R.
Wakefield, J. D.
Waldorf, S. K.
Wallis, W. F.
Walsh, James E., Jr.
Walton, Matt
Waring, G. A.
Watt, Walter L.
Watt, William George
Weber, Wm.
Weightman, R. H.
Weiler, H. R.
Weitz, John H.
Wells, Francis G.
Wells, H. W.
Wells, Roger C.
Wengerd, Sherman Alexander
Wenner, F.
Wenzel, Leland K.
Whitcroft, Thomas H.
Whitten, C. A.
Wilcox, Burt W.
Wiles, William E.
Wilgus, Austin S.
Williams, Howard M.
Williams, Mrs. Lucille A.
Williams, Lucretia
Williamson, Philip H.
Williamson, R. O.
Willis, John E.
Willson, Betty May
Wilson, R. M.
Wilson, Ralph N.
Wilson, Walter T.
Winslow, Allen G.
Woolhiser, J. E.
Woollum, Clarence A.

Yeager, W. Hayes

Zies, E. G.
Zietz, Isadore
Zimmer, M. L.
Zitler, Helen E.
Zoch, Richmond T.

APPENDIX B--REPORT OF GENERAL SECRETARY OF THE AMERICAN GEOPHYSICAL UNION TO THE GENERAL ASSEMBLY, TWENTY-FOURTH ANNUAL MEETING, APRIL 24, 1943

Membership--Thanks to the efforts of the Committee on Membership (G. W. Musgrave, Chairman), the net increase in membership is 380 since April 1942; the total number of active members on April 24, 1943, is 1898. Figure 1 shows graphically the rapid increase in membership of the Union for the three decades beginning in 1921--it emphasizes not only the fruitful activity of our successive Committees on Membership but also the rapid growth of interest in geophysical sciences in the United States. The growth since April 4, 1942, is noteworthy, account being taken that, because of the war, a greater number than usual (30) of our members asked to be placed on the inactive list during the year. Five members were reinstated from the inactive list, ten were dropped because of non-payment of dues for two years, and 12 have died [as reported to the General Assembly by the General Secretary (see p. 9)]. Senor Alfonso Contreras Arias of Mexico, an outstanding investigator in the fields of meteorology and hydrology, was elected a Corresponding Member of the Union and was presented with a certificate on January 11, 1943.

Executive Committee meetings--The Executive Committee held one well-attended meeting September 18, 1942, for consideration of the Union's business. At that meeting special attention was given to the relations of the American Geophysical Union with the International Union of Geodesy and Geophysics and with the International Meteorological Organization.

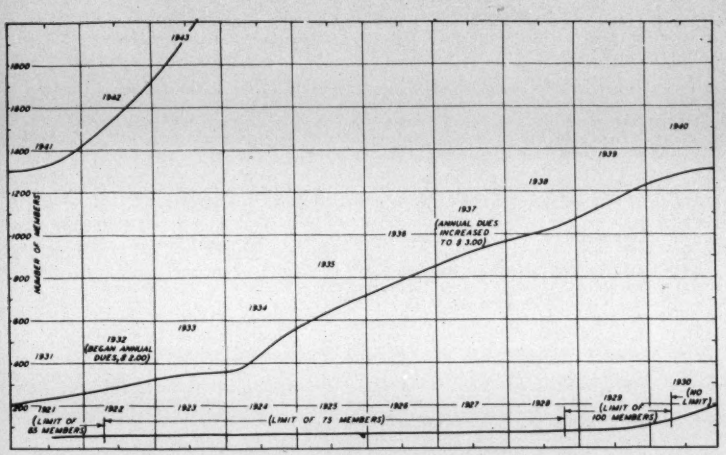


Fig. 1--Curve of membership, noting dates of increase in membership-limit and origin and increase of annual dues, American Geophysical Union, 1921-43

Meetings--The Twenty-Fourth Annual Meeting of the Union and its Sections was arranged for April 23 and 24, 1943. President Cloyd Heck Marvin of the George Washington University again extended the Union the courtesy of the facilities of the Hall of Government of the University. As in 1942, the meeting was curtailed to two days, but despite this the program of scientific sessions included 107 papers and progress-reports. The arrangements for this meeting were made by a committee of seven members under the energetic chairmanship of J. Putnam Marble.

The Fifth Award of the William Bowie Medal was made at the general conference on April 24 to Oscar E. Meinzer, preeminent for his contributions to scientific hydrology.

Regional meetings planned for Salt Lake City and Berkeley in 1943 were postponed because of the war. It is planned, however, to hold a regional meeting at Corvallis, Oregon, on June 16, 1943.

Publications--The publication of a revised list of members and officers to replace the printed list of February 15, 1942, was postponed pending receipt of information requested by a circular letter as to latest addresses. Changes of address were unusually numerous because many of our members joined the military establishments and bureaus.

The Transactions of 1942 totaled 741 pages (equivalent to 1,100 pages in ordinary printer's format) in two parts. Part I (171 pages) contains reports and papers of joint regional meetings of the Section of Hydrology at Dallas, Texas, December 30, 1941, and at Pasadena, California, January 16-17, 1942, and was off the press in August 1942; part II (570 pages) contains the proceedings of the General Assembly and all Sections at the Twenty-Third Annual Meeting held at Washington, D. C., April 3 and 4, 1942, and was off the press in November 1942 but delays in the bindery prevented completion of delivery until late in December. An entirely new format was used for the Transactions of 1942, the master-copy being prepared on a proportional-spacing typewriter manufactured by the International Business Machines Corporation. Despite the increased cost of paper and labor, the total outlay for preparation and printing of the Transactions of 1942 for an edition of 2,000 for part I and 2,200 for part II was $3,183.11, or at an average cost per set of about $1.50. As in past years, complete sets were sent not only to members and authors but also to libraries and scientific organizations for review, and a stock was set aside for future distribution to our colleagues abroad when conditions permit.

A 64-page publication giving the proceedings of the Seventh General Assembly of the International Association of Geodesy at Washington in 1939 was prepared and distributed. It was found

impossible to complete this work in France and it was deemed desirable by all concerned that the proceedings should be distributed promptly to geophysicists in the Western Hemisphere and in others of the United Nations.

The Union's publication "Bibliography of Hydrology of the United States of America" for the years 1941 and 1942 was necessarily postponed because of the dearth of editorial assistance in compiling the references. It is expected, however, that as soon as opportunity permits, the sixth Bibliography continuing the series already published for the years 1935 and 1936, 1937, 1938, 1939, and 1940 will be prepared for the years 1941, 1942, and 1943.

It has been proposed that there be prepared and published a complete index of titles and authors of the 20 volumes of Transactions so far published by the Union containing a total of over 9,000 pages. In view of the many valuable contributions and references thereto, this proposed index would be most useful for investigators in geophysical and kindred subjects.

Representation on Divisions of the National Research Council and other organizations--The three-year terms of N. C. Grover, C. O'D. Iselin, and T. G. Thompson of the American Geophysical Union to the Division of Foreign Relations of the National Research Council expired June 30, 1942. J. E. Church, P. C. Whitney, and T. G. Thompson were appointed for the three-year period 1942 to 1945. The membership of the Union in this Division is now as follows: J. E. Church, R. M. Field, J. A. Fleming, N. H. Heck, W. C. Lowdermilk, T. G. Thompson, and P. C. Whitney.

It has long been recognized by the Division of Geology and Geography of the National Research Council and by the Union that the Union should have a representative on that Division so that those intimate relations of geophysics with geology might be emphasized in the Division's activities. Upon the invitation of Chairman W. H. Bucher of the Division, the Executive Committee of the Union designated the General Secretary of the Union to be its first representative on the Division.

At the request of the Director of the Foundation for the Study of Cycles, E. H. Vestine of the Union was designated as a member of the Advisory Committee of that Foundation on matters pertaining to cycles and in particular to the designation of recipients of the Foundation's medal for the most valuable contribution to any line of cyclic research during 1943.

At the request of Director Carmichael of the National Roster of Scientific Personnel of the Office of Emergency Management, President Lowdermilk, Vice-President Adams, General Secretary Fleming, and Messrs. Musgrave and Garner were designated as consultants from the American Geophysical Union in matters bearing on geophysical personnel.

Finances--The report [see Appendix I] of the Committee on Audit for the calendar year 1942 showed the correctness of the records of receipts and disbursements. The total of receipts, including the balance from 1941 of $6,008.34, was $12,651.76, while the total of disbursements was $5,870.41, leaving a balance of $6,781.35 as of December 31, 1942. This balance includes $1,513.77 from funds of the Washington Assembly obligated in full for reprints of the proceedings of the International Associations of Seismology, Scientific Hydrology, and Volcanology.

The receipts from January 1, 1943, to April 24, 1943, were $11,764.53 (including balance carried over of $6,781.35 and receipts of $4,983.18), while the disbursements were $3,448.65; thus there is a total available balance of $8,292.88 on April 24, 1943.

As in previous years, the National Research Council assisted the Union by a grant of $400 for the fiscal year ending June 30, 1943.

Miscellaneous--Since September 1942 President W. C. Lowdermilk has been on a special mission to China, and Vice-President L. H. Adams has acted in his place.

The President of the Union was asked to attend the dedication of the Mineral Industries Building of the University of West Virginia at Morgantown, West Virginia, on October 16-17, 1943. Because of his inability to attend, a congratulatory message was sent on behalf of the Union.

International Union of Geodesy and Geophysics--Despite the interference because of the war with the complete functioning of the International Union of Geodesy and Geophysics, it was possible, through the efforts of the officers of the International Union in Great Britain and those in the United States, to preserve a considerable part of the functioning of the International body and thus insure its continuance and the certainty of resuming its important work promptly upon the termination of the war. At present, of the 33 adhering nations 17 are Allied or neutral countries

and 16 are Axis or Axis-controlled countries. The Presidents of the Associations of Seismology and of Terrestrial Magnetism and Electricity are Messrs. Heck and Fleming of our Union, and Lambert is a member of the Executive Committee of the Association of Geodesy. Professor R. M. Field is Chairman of the International Commission on Continental and Oceanic Structure, and Dr. J. E. Church is President of the International Commission of Snow. These men have found it possible to carry on and keep alive many of the normal operations concerned. The conditions were not so favorable in the Associations of Scientific Hydrology and Volcanology since the officers of these Associations are in occupied countries; Dr. O. E. Meinzer, however, is Chairman of the International Commission on Subterranean Waters of the former and Dr. T. A. Jaggar is a Vice-President of the latter. For the Association of Meteorology, the United States is fortunate in having Professor J. Berknes in this country so that the interests in meteorology are being followed. For the Association of Oceanography, Dr. J. Proudman of Liverpool is Secretary, so that continuity of the Association's activities is assured. Professor E. Rothé, Secretary of the Association of Seismology, died in 1942; fortunately his work is being continued by his son. President D. la Cour of the International Union died May 19, 1942; under the circumstances, it has not been possible to arrange for the election of a successor but the general functioning of the Union has been maintained through its General Secretary, H. St. J. L. Winterbotham.

The general session of the Twenty-Fourth Annual Meeting of the Union on the afternoon of April 24, 1943, was devoted to a conference on the projected program of the International Commission on Continental and Oceanic Structure. This Commission was formed at Edinburgh in 1936 with the instruction to devise, stimulate, and sponsor geophysical-geological studies of crustal structure on a world scale, in extension and in support of the similar but less extensive studies made by some of the national organizations adhering to the International Union of Geodesy and Geophysics. Briefly, these may be summarized as follows: (1) Nature and causes of regional magnetic patterns and anomalies; (2) nature, distribution, and dynamic causes of regional and gravitational anomalies; (3) nature and causes of regional and temporary variations in radio transmission and reception; (4) nature and dynamic causes of crustal deformation-patterns such as may control regional occurrence or non-occurrence of valuable mineral resources; (5) relation between possible cosmic cycles or rhythms and possible prediction of long-period rhythms as affecting climate and weather; (6) relations of relative climate, hydrology, and soils. Authority was given by General Secretary Winterbotham of the International Union for expenses of the International Commission in the furtherance of its objectives by providing $1,000 proportioned according to the contributions of the several adhering nations. The members of this Commission (as of August 1943) are R. M. Field (Chairman), J. A. Fleming (Secretary), A. Angenheister, B. Gutenberg, W. A. Heiskanen, B. Helland-Hansen, H. H. Hess, O. T. Jones, Harold Jeffreys, M. Matuyama, H. U. Sverdrup, and F. A. Vening Meinesz; of these, because of the war, Messrs. Gutenberg, Hess, and Sverdrup act as alternates for Messrs. Angenheister, Vening Meinesz, and Helland-Hansen, respectively.

It is to be recalled that the American Geophysical Union has made free distribution of some 300 to 400 copies of its Transactions each year to members abroad of the International Union of Geodesy and Geophysics. Because of postal regulations during the war, this distribution has been somewhat restricted since 1939; the Union is holding about 200 to 300 copies of each volume for distribution when opportunity permits.

In the field of snow, the avalanche film, which was received from Switzerland through the Swiss Legation last year by President Church of the International Commission of Snow, has proved most valuable, especially in connection with war studies and training concerned with transportation and study of snow and avalanche conditions.

J. A. Fleming, as a Vice-President of the International Union of Geodesy and Geophysics, continued in charge of the International Union's funds from the United States. During the year $198.70 was paid to the American Geophysical Union for the share of the International Association of Scientific Hydrology in printing the Bibliography of Hydrology of the United States of America for 1940 and $100 against expenses of the International Commission on Continental and Oceanic Structure.

The quota of $3,920.40 for adherence of the United States to the Union was authorized for payment but, because of a blunder, the check was sent to London and arrangements are now under way for its return through the American Embassy in London for deposit with other funds here. On April 24, 1943, the balance on deposit with the Riggs National Bank was $6,432.52. [Since preparation of this report $3,920.40 for last year's quota was received from London and the balance is $10,352.92--practically the whole United States quota for the calendar years 1939, 1940, and 1941.]

The American Geophysical Union has made every endeavor in the past year to increase coordination and collaboration of interests, especially with the geophysicists of the Western Hemisphere, and, as indicated above, to maintain a considerable part of the continuity of the functions of the International Union of Geodesy and Geophysics, thus protecting for the future International relations so essential to geophysical investigations. A recent quotation from a prominent geophysicist of California may be apt in this connection: "The Union, in my opinion, is to be congratulated for having the vision and courage to proceed with the (24th) annual meeting. The Nation needs more, not less, scientific endeavor."

J. A. FLEMING, General Secretary,
American Geophysical Union

APPENDIX C--REPORT OF COMMITTEE ON MEMBERSHIP

R. R. Bodle, L. P. Disney, J. A. Duerksen, L. P. Harrison, H. F. Johnston, W. E. Smith, J. S. Vhay
G. W. Musgrave, Chairman

The Committee has had the cooperation of numerous officers and Members of the Union, and for this it desires to express most sincerely its deep appreciation.

A total of 439 new Members were favorably reported between April 1942 and April 17, 1943, representing a gross gain of 29 per cent for the period. The distribution of the 439 new Members by Sections is shown in Table 1.

Table 1--Gain in affiliations by Sections, April 1942 to April 1943

(Designations of Sections: (a) Geodesy; (b) Seismology; (c) Meteorology; (d) Terrestrial Magnetism and Electricity; (e) Oceanography; (f) Volcanology; (g) Hydrology; (h) Tectonophysics)

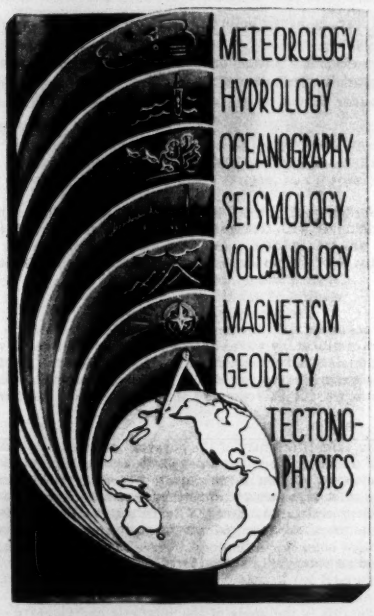
Item	Section								Total
	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	
Members, April 1942	236	351	523	283	264	210	863	341	3071
New Members, April 1942 to April 1943	102	58	165	99	84	29	210	55	802
Increase, per cent	43.2	17.5	31.5	35.0	31.8	13.8	24.3	16.1	.....

When this Committee began its work there was some doubt that much room for expansion of membership existed. The thought had been expressed that geophysicists were not numerous and that expansion of membership might result in lowered standards for membership. Several rough studies were made of the situation. For example, it was apparent that, while we had Members in all of the States and most of the Territories and Island Possessions, there were high concentrations in certain areas and marked deficits in others. On the basis of number of Members per million of population, the 20 leading political subdivisions are District of Columbia, Hawaii, Utah, Maryland, California, Colorado, Oregon, Massachusetts, Texas, Virginia, Oklahoma, Washington, New Jersey, Iowa, New York, Pennsylvania, Tennessee, Illinois, Ohio, and Missouri. Note that California, Colorado, and Oregon (with 26.8, 26.7, and 22.0 Members per million of population, respectively) rank much above Illinois, Ohio, and Missouri (with only 5.6 , 5.4, and 4.8, respectively). There is no obvious reason why Missouri, for example, should rank below Oregon on the basis both of absolute number of Members and of Members relative to population. Not included among the leading 20 are Indiana, Kansas, Michigan, Minnesota, and Wisconsin; these are States ranked high by J. McKeen Cattell as producers of scientific men. Every examination of this kind indicates that there is ample room for growth and that we need have no fears of lowered standards.

The Committee prepared and there was printed for wide-spread distribution among our Members and persons fully qualified to become Members a circular regarding the Union, its purposes, and general descriptions of the functions of each of the eight Sections with a somewhat definitive schedule of the theoretical and applied interests of each Section. This four-page circular is reproduced on pages 297-300. It has been most useful in furnishing interested persons and organizations with information on the opportunities and potentialities of the Union's activities throughout our country.

REPRODUCTION OF CIRCULAR

To promote the study of problems concerned with the figure and physics of the Earth, to initiate and coordinate researches which depend upon international and national cooperation, and to provide for their scientific discussion and publication



You who are interested in any of the theoretical or applied sciences relating to the Earth, its configuration, its structure, and the natural forces in operation upon or within it, have an interest in the American Geophysical Union, which attempts to bring all such interests into a common focus. Since the inception of the American Geophysical Union in 1919, the organization has gradually developed so that now it is perhaps the principal organization in the country acting as a clearing house for new thoughts and ideas relating to geophysics.

Sponsored by the National Academy of Sciences through the National Research Council, the Executive Committee of the Union is the Committee on Geophysics of the Council and is the American Committee of the International Union of Geodesy and Geophysics. Among the functions of the Union is that of initiating and coordinating researches which depend upon international and national cooperation and to provide for their scientific discussion and publication.

Its eight Sections and their special interests, as listed below, embrace a tremendous field which is expressed in the papers presented at the annual meeting each spring, in the regional meetings (often held in cooperation with other scientific organizations), and in the "Transactions" of the Union issued in several Parts each year. Symposia on timely subjects are frequently presented. The annual dues are $3.00, which includes subscription to all of the Parts of the "Transactions", as well as the other privileges of membership.

In these days of total war, as never before, American scientific workers need to affiliate and to carry forth the bright light of truth and science. Responsibility for such action falls with particular directness upon Americans. Now as never before, American scientists personally benefit by affiliation with their fellow specialists and co-workers, since the individual worker is under a great handicap. Now as never before, scientists in general need to affiliate and play their proper part in world affairs.

THE SECTIONS OF THE UNION

(a) GEODESY

This Section of the Union is devoted to large-scale surveying on the Earth's surface, dealing particularly with triangulation, leveling, and gravimetric surveys. Its objectives are principally determining the shape and size of the Earth and adequate mapping of the Earth's surface. Borderline subjects are earth-tides and variations of latitude.

(b) SEISMOLOGY

This Section is concerned with the solution of problems related to earthquakes and the transmission of vibratory waves through the Earth. It deals with the internal constitution and surface structure of the Earth. The Section is of interest to the geophysicist, the geophysical prospector, the foundation engineer, the structural engineer, the geologist, the astronomer, and the insurance executive.

(c) METEOROLOGY

Meteorology is the scientific study of the physical processes which occur in the atmosphere and of the connected processes of the lithosphere and hydrosphere. It seeks to provide an understanding of the causes of weather and climatic conditions and their changes. These exert a profound influence on the entire course of existence of everything living or inanimate on the Earth's surface and in its gaseous envelope. Meteorology is therefore of universal interest, including, as it does, all branches of pure and applied science, technology, agriculture, business, communications and transport, and military and naval strategy and tactics.

(d) TERRESTRIAL MAGNETISM AND ELECTRICITY

The field of this Section is the study of the magnetic and electric phenomena of the Earth's interior and atmosphere. The Section has experienced new growth during recent years because of developments in radio communication in which the magnetic and electric properties of the outer atmosphere play a vital role. Cosmic radiation likewise comes into the field of the Section. The intimate connection between the electrical and magnetic conditions of the Earth and various solar phenomena has caused many astrophysicists and solar physicists to affiliate with the Section.

(e) OCEANOGRAPHY

Covering the greater part of the Earth, the sea has a profound effect on man and the world in which he lives. In their interaction with the atmosphere, the oceans exercise a marked influence over climate and vegetation. The configuration of the ocean bottom and the action of tides and currents have an important bearing on maritime activities. Oceanic movements together with the physical and chemical properties of sea water affect marine life and thereby influence fisheries. The sea thus presents a field of research not only for the oceanographer but also for workers in bordering branches of science.

(f) VOLCANOLOGY

The Section of Volcanology encourages research and the presentation of papers not only in "pure" volcanology but also in many fields such as the study of volcanic and intrusive rocks, relation of ore-deposits to igneous activity, and laboratory experiments on processes of volcanism and the formation of igneous rocks and ore-deposits.

(g) HYDROLOGY

The Section of Hydrology deals with the distribution and disposal of precipitation on the land areas of the Earth, and as such is a borderline science of interest to agronomists, engineers, foresters, meteorologists, soils technicians, geologists, and others, and thus forms a meeting ground for all those who are concerned with any phase of hydrology. Its membership has contributed much in the decade since its inception in 1931 to theories of precipitation, runoff, infiltration and percolation, movement of flood-waves, soil erosion and the transportation and deposition of sediment, density-currents, the behavior of ground-water, evapo-transpiration, glaciers, the physics of soil moisture, and the development of useful techniques for dealing with hydrologic problems.

(h) TECTONOPHYSICS

The Section of Tectonophysics coordinates the application of physical methods and geologic and geophysical data to the solution of problems of Earth structure, through laboratory experiments, geologic observations, and theoretical analyses.

FIELDS OF INTEREST OF THE SECTIONS

(a) GEODESY

- Determination of shape and size of Earth
- Triangulation
- Precise leveling
- Mapping
- Gravimetric surveys and prospecting
- Earth-tides
- Variation of latitude
- Photogrammetry

(b) SEISMOLOGY

- Solution of problems of earthquakes
- Transmission of vibratory waves through the Earth
- Internal constitution of the Earth
- The surface structure of the Earth
- Seismic prospecting

(c) METEOROLOGY

Practical meteorology

Methods, data, forecast, and other applications

Physical properties, composition, and general structure of the atmosphere

Structure, mechanics, and thermodynamics of the atmosphere in general; radiation and temperature; atmospheric pressure; wind; water vapor and hydrometeors, fog, clouds, and precipitation; soil moisture and hydrology; hydrometeorology

Climatology

Solar climate, climatic zones, influence of latitude; variations of climate; microclimatology; types of climate; bioclimatology; climatology of the free atmosphere; influence of environment

Various phenomena and influences

Cosmical influences; visibility through the atmosphere; optical, electrical, and acoustical phenomena in the atmosphere

(d) TERRESTRIAL MAGNETISM AND ELECTRICITY
- Magnetic and electric phenomena and properties of the Earth and the atmosphere
- Permanent geomagnetic fields; variable fields, internal and external
- Natural electric earth-currents; earth-resistivity
- Electric fields of the atmosphere, average and variable aspects
- Electrical properties of the atmosphere including the ionosphere
- Relations to cosmic phenomena
- Isomagnetic and isoelectric charts and applications to navigation, wired and wireless communication, determination of subsurface geology and ore-deposits

(e) OCEANOGRAPHY
- Configuration of oceanic basins
- Deposits of the ocean bottoms
- Physical and chemical properties of sea water
- Waves, tides, currents, and related phenomena

(f) VOLCANOLOGY
- Origin of igneous rocks
- Geochemistry
- Volcanic activity and products
- Mechanics of intrusion
- Petrography
- Experimental petrology
- Ore-forming fluids and solubility of elements in them

(g) HYDROLOGY
- Precipitation
- Runoff
- Infiltration and percolation
- Evaporation and transpiration
- Chemistry of natural waters
- Ground-water
- Soil moisture
- Dynamics of streams
- Transportation and deposition of sediment
- Movement of flood-waves
- Limnology
- Glaciers

(h) TECTONOPHYSICS
- In the laboratory
- Determination of physical constants of rocks and minerals
- Deformation of minerals, including ice
- Deformation of rocks
- In the field
- Metamorphic processes
- Observed nature and behavior of the crust
- World-wide tectonic patterns
- Mechanics of glacier flow
- Forces available for crustal deformation

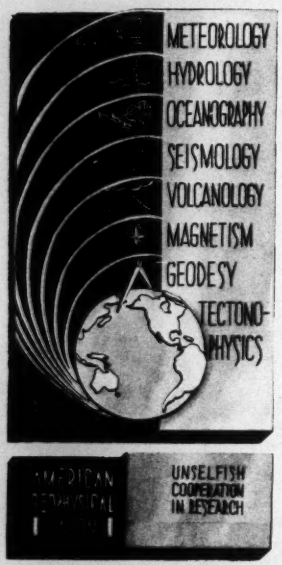
Proposal forms with information regarding qualifications and requirements for election as Member or Associate Member may be secured from

The General Secretary, American Geophysical Union,
5241 Broad Branch Road, Northwest,
Washington 15, D. C.

After you have examined this circular, please pass it on to a friend who may be interested in membership in the AMERICAN GEOPHYSICAL UNION

AMERICAN GEOPHYSICAL UNION

CERTIFICATE OF CORRESPONDING MEMBERSHIP



Washington, D.C., U.S.A.

In recognition of outstanding achievement in

the Executive Committee of the American Geophysical Union has on this day elected

a Corresponding Member of the Union

General Secretary President

Chairman, President Section
Membership Committee

To promote the study of problems concerned with the figure and physics of the Earth, to initiate and coordinate researches which depend upon international and national cooperation, and to provide for their scientific discussion and publication

Our experience repeatedly shows that many well-qualified workers have never received personal invitations to apply for membership nor have they had offers of sponsorship for proposal forms. The Members of the Union are in excellent position both to judge the qualifications of other workers in their respective fields and to extend personal invitations to those who do qualify. In the long-time view, natural and healthful growth can be best secured through the continued activity of the membership at large. The Members of the Union are to be commended for the work they have done during the past year; their continued interest should be encouraged to the fullest extent.

A new class of Corresponding Members was established with the approval of the Executive Committee for the purpose of effecting closer contacts through the election to this class of distinguished geophysicists of foreign citizenship. A facsimile of this Certificate is given on page 301; as will be noted, Corresponding Membership is limited to persons who have accomplished outstanding achievement in any or all of the activities of the eight Sections of our Union. The first Corresponding Member elected was our Mexican colleague, Señor ALFONSO CONTRERAS ARIAS, distinguished investigator in meteorology and hydrology. The Certificate was presented to him in Washington, January 11, 1943, by Vice-President ADAMS.

APPENDIX D--REPORT OF COMMITTEE ON STATUTES AND BY-LAWS

L. V. Judson E. W. Woolard
H. D. Harradon, Chairman

At the meeting of the Executive Committee on September 18, 1942, the Chairmen of the Committees on Membership and on Statutes and By-Laws were instructed to consider alterations in the Statutes which would legalize the admission into the Union of citizens of countries other than the United States and thus clarify the Statutes in this respect. At the request of Chairman MUSGRAVE of the Committee on Membership, certain tentative modifications in the Statutes were suggested for the consideration of his Committee. Changes which that Committee thought would cover all contingencies were submitted January 11, 1943. These were considered and, after a few minor alterations in phraseology by the Committee on Statutes and By-Laws, were approved by the Chairman of the National Research Council on January 14, 1943. These recommended changes are being submitted to the Executive Committee for action at its next meeting.

APPENDIX E--REPORT OF COMMITTEE ON BUDGET

R. W. Goranson H. N. Eaton
C. H. Swick, Chairman

Your Budget Committee wishes to submit the following proposed budget for the fiscal year July 1, 1942, to June 30, 1943:

EXPECTED RECEIPTS		
Balance in bank, July 1, 1942	$6,110.89[b]	
Dues, 1500 (net[a]) members for 1942	4,500.00	
Grant, National Research Council	400.00	
Sales, Transactions and reprints	1,500.00	
Sales, copies of geophysical-geological maps	0.00	
Total		$12,510.89
AUTHORIZED EXPENDITURES (not to exceed)		
Cost 1942 Transactions complete (600 pp. est.) and reprints	$3,200.00	
Cost of Bibliography of Hydrology for 1941	0.00[c]	
List of Members	250.00	
Clerical services, including full-time stenographer in General Secretary's office, and for Sections	2,500.00	
Expenses 24th Annual Meeting	400.00	
Expenses Regional Meetings	150.00	
Committee expenses	400.00	
Postage (Transactions, reprints, and office)	500.00	
Stationery and miscellaneous	500.00	
Reserve for contingencies, initiation of American Journal of Geophysics, and balance	4,610.89	
Total		$12,510.89

[a]Although we have now some 1600 members and prospective increase, effects of war causing resignation and non-payments of dues, make wise to set net of dues as for 1500 members.

[b]Exclusive of (a) Bowie Medal Fund $203.60 and (b) Special Fund $207.00.

[c]Probably no manuscript will be prepared for 1941 until after war; if an edition for 1941 is prepared, cost will be equaled by sales.

APPENDIX F--REPORT OF COMMITTEE ON MEETINGS

Merrill Bernard C. L. Garner Glenn L. Parker
G. B. Cressey R. A. Hertzler W. D. Sutcliffe
John Putnam Marble, Chairman

In accordance with the recommendation of the Executive Committee, the Twenty-Fourth Annual Meeting of the American Geophysical Union was held on April 23 and 24, 1943. All Sections met and conducted programs of contributed papers. The Annual Business Session of the Union was held at 12:15 o'clock, April 24. On the afternoon of April 24, at the request of Dr. RICHARD M. FIELD, Chairman of the Commission on Continental and Oceanic Structure of the International Union of Geodesy and Geophysics, a conference was held, at which Dr. Field, representatives of the eight Sections of the American Geophysical Union, and interested Members discussed possible future cooperation between the Sections of the Union and the Commission. This conference was the last item of the formal General Assembly of the Union, at which the William Bowie Medal was awarded and memorials to Members deceased during the past year were read. Because of the preoccupation of many of the Members with war work, the usual evening public lecture and smoker were not held.

All the meetings were held in the Hall of Government of The George Washington University, Twenty-First and G Streets, Northwest, Washington, D. C., by the kind permission of President CLOYD HECK MARVIN. The effective cooperation of the University authorities is deeply appreciated.

APPENDIX G--REPORT OF SPECIAL COMMITTEE FOR COOPERATION WITH INTERNATIONAL COMMISSION FOR STUDY OF TIDAL WAVES

P. Byerly H. N. Eaton W. F. McDonald
L. P. Disney, Chairman

The tide stations maintained along the Pacific Coasts of Central and South America on a cooperative basis by the several American Republics and the United States Coast and Geodetic Survey are furnishing some interesting records of seiche movements arising from seismic disturbances.

On the basis of instrumental reports, an earthquake occurred on the coast of Peru at $17^h\ 50.7^m$, 75° west meridian time, August 24, 1942, with location of epicenter approximately 14°.5 south latitude, 75°.5 west longitude. This location is about midway between the ports of Callao and Matarani.

Seiches set up by this earthquake were recorded on the marigrams of the tide stations located at Callao and Matarani, Peru, and Valparaiso, Chile--the last over 1,000 miles from the epicenter. Information tabulated from the marigrams is given in Table 1.

Table 1--Data on seiches set up at South American stations by earthquake of August 24, 1942

Station	Time of arrival, 75° west mer. time	Duration	Average range	Maximum range	Period
	hr	hr	ft	ft	min
Callao, Peru	19-1/2	18	2	4	30
Matarani, Peru	18-1/2	12	1	2	15
Valparaiso, Chile	20-3/4	6	..	1/2	Indefinite

Word was received through Captain N. H. HECK of the death of M. H. HUBERT, Secretary of the International Commission for Study of Tidal Waves, on November 14, 1941. Mr. Hubert had charge of the compilation of material from the various International Committees and the publication of the "Annales de la Commission pour l'Etude der Raz de Marée". The belated report of his death emphasizes the loss of all contact with the International Commission. Under present world conditions, it is believed that the Special Committee for Cooperation with International Commission for Study of Tidal Waves can no longer serve the purpose for which it was organized. It is recommended, therefore, that this Special Committee be terminated.

APPENDIX H--REPORT OF SPECIAL COMMITTEE ON GEOPHYSICAL AND GEOLOGICAL STUDY OF CONTINENTS

L. H. Adams
Perry Byerly
M. G. Cheney
R. A. Daly
E. DeGolyer
Maurice Ewing
J. A. Fleming
C. L. Garner
Beno Gutenberg
N. H. Heck
H. H. Hess
F. W. Lee
A. I. Levorsen
C. R. Longwell
J. B. Macelwane
Paul H. Price
L. B. Slichter
H. T. Stetson
W. H. Twenhofel
B. B. Weatherby
G. P. Woollard
W. T. Thom, Jr., Chairman

Introduction

Between December 7, 1941, and March 7, 1943, the intellectual and material energies and resources of the United States have been almost wholly absorbed in putting the nation on a war footing, but now that this total mobilization is almost complete we are obviously passing on to a new phase in which our intellectual mobilization for the coming peace is getting under way, almost simultaneously with the inception of full-scale American participation in the active fighting. Every scientist and every scientific unit and society naturally can make some contribution toward the planning and establishment of a rational, prosperous, and peaceful world-order, and it is the hope of this Special Committee that its ideas and efforts may contribute to the efforts of the American Geophysical Union, as a whole, to fulfill its corporate responsibilities to our National Research Council and to the International Union of Geodesy and Geophysics, and through them to the program of the United Nations.

In order to reduce the Committee's ideas and suggestions to specific form, seven programs are outlined below, upon which some work has been done and upon which more progress can be made with relative facility and speed.

Program 1

A program for the further study of the relationships between gravitational anomalies and tectonic disturbances--Even since Dr. VENING MEINESZ and his coworkers demonstrated that gravitational "negative anomaly-strips" were characteristic features of the more active parts of the East Indian and West Indian island-arc areas, and ever since the tectonic significance of these "anomaly-strips" became clear, it has been obvious that many more first-order and second-order gravity stations are needed over the whole Globe: (a) Partly to give us three-dimensional information on present and past arc-systems; (b) partly to give us clear quantitative evidence on both the general perfections of isostatic adjustments and the local occurrence of significant anomaly-systems; and (c) partly to give us a quantitative basis for analyzing the mechanical conditions and causes responsible, for instance, for the movements of elevation and tilting which have gone on since the Pleistocene ice-sheets vanished from Scandinavia and from the Great Lakes and Eastern Canadian regions.

This program looks forward to the completion of a full grid of first-order pendulum stations set at convenient locations, on a spacing of approximately 50 miles, with a supplementary net of second-order (gravimeter) stations spaced at intervals of about five miles. Such a double system of gravity stations would beyond question provide a great deal of general factual data about: (a) Crustal compositions and subcrustal flow; (b) the form and pattern of many buried topographic features; and (c) the trends and characteristics of the buried extensions of locally-visible orogenic features. A great wealth of even more detailed (and revealing) evidence indicating local geological-gravitational correlations will also become available, when the results of commercial gravitational surveys have ceased to be of competitive importance.

Recent reports which demonstrate the importance of the field of gravitational research include ones by LAWSON on the Sierra Nevada, MILLER on Gravity variations in Eastern Canada, LONGWELL on Gravity conditions in Southern New England, WOOLLARD on Gravity conditions in parts of the North Atlantic Coastal Plain, and ASLAKSON and SWICK on Gravity conditions in parts of the Andean zone of northern and western South America.

It should be noted, in connection with this study, that it is reliably reported that mechanical gravimeters are now in operation which can give quick readings to about 0.02 milligal, and that this order of sensitivity is proving of great use in certain regions.

However, in order that these highly sensitive gravimeters can be used to full advantage, it will be necessary to determine the magnitude of the Earth-tide influences upon such gravimeters by series of continuous-record observations of fixed gravimeters in different regions. In a paper read before the Society of Exploration Geophysicists on April 7, 1943, LOCKENWITZ of the University of Texas described the results of such an experiment to test the effect of tidal forces upon a stationary gravimeter. Using a stationary gravimeter (specially jacketed to eliminate temperature effects), curves were obtained which showed variations of the force of gravity with time, clearly indicating the existence of a measurable influence of the Sun and Moon. The magnitude of this tidal effect was about ten per cent larger than was theoretically predictable. This residual effect showed a phase-lag with reference to the direct solar-lunar tidal effect. It seemed especially noteworthy that the amplitude and phase of the residual component as obtained at Austin differed somewhat from those determined previously in a similar experiment in the Gulf Oil Corporation's laboratories in Pittsburgh, and it was suggested that these response-differences were due to differences in crustal composition and structure at the two localities. It was concluded, therefore, that, for a proper study of Earth-tides, observations should be made with stationary gravimeters and tilt-meters at a number of critical localities.

Program 2

A program for the study of the present rates of progression of differential horizontal crustal movements--It has been generally assumed that differential horizontal movements between crustal segments are negligible at the present time--even though it is also generally recognized that such movements have gone on more or less continuously throughout geologic time, with the production of overthrust faults and lateral displacements measurable in tens of miles. However, evidence has now accumulated to a point where it is reasonably clear that appreciable differential crustal shifting is still going on in different parts of the world, and it, therefore, seems highly expedient that adequate data as to the nature, magnitude, and distribution of these relative movements should be obtained forthwith because of the critical bearing of these data upon overall geodetic and cartographic programs and operations.

The nature and (partial) magnitude of old crustal shiftings have been recorded in many geologic descriptions of the various mountain systems of the world, and the presence of great rift or shift-zones in continental shield-areas was graphically indicated by Dr. A. W. JOLLIFE'S paper given at last year's Tectonophysics' Symposium [Trans. Amer. Geophys. Union 1942, pp. 699-707], in which he published photographs and maps depicting a part of the displacement-fractures which feature the "exposed-shield" area of northwestern Canada. As stated by Dr. Jolliffe:

> "Many faults in the Canadian Shield are known to follow essentially rectilinear vertical fractures that extend for distances up to several hundreds of miles. None of them is known to be marked by major vertical displacements whereas a number show strike-slip movements amounting to several miles. From this it is inferred that the fault-movements were dominantly horizontal, of the same general nature as those along the San Andreas Rift. Movements along many of the Shield faults were recurrent, the most recent being Late Pre-Cambrian or even younger in age. Important ore-deposits (Noranda, Yellowknife) may be related to some of the faults."

Numerous recent studies of fault-movements in California, made by BUWALDA, BYERLY, GUTENBERG, and others, have given clear indication that systematic differential movements are going on as between a general crustal segment along the Pacific Coast and west of Owens Valley, and a continental segment to the east, this latter block tending to move differentially toward the southeast with respect to the coastal segment. Some hint as to the quantitative magnitude of such movements is available from the Buena Vista Oil-Field, where continuing movements along a subsidiary thrust-fault cause buckling and deformation of pipe-lines crossing the fault-trace, as well as bending and shearing of the steel casing in oil-wells which pass through the thrust-plane.

Because of the importance of this problem of crustal shift to geodetic, geologic, and astronomic science, the following three steps should be taken as soon as possible:

(1) A number of particularly suitable test-areas should be chosen for study and should be covered by closely-spaced triangulation-nets, and repeat-observations should be made in these areas at intervals of a year or two, throughout a considerable period of years.

(2) Consideration should be given to the possibility of extending the California system of seismic studies to the other areas chosen for similar geodetic-seismic-tectonic study.

(3) Further compilations of photographs and maps should be made, in order to secure more regional data on fault-patterns and relationships, and more quantitative data as to the magnitude

and relative directions of crustal shiftings--past and present. (A great deal of assistance with such a project can probably be had through the development of suitable collaborative arrangements with geoscientific agencies and workers abroad, and especially with those of Canada, since Canada has long been an active pioneer in the collection and use of airplane photographs as a basis of map-making and geoexploration.)

Program 3

A program for a further study of the relations between geomagnetic variation, local geologic structure, and tectonic movement--There seem to be several reasons for expecting that the further study of local and regional magnetic variations in critical continental areas may be of great assistance in solving several of geology's most fundamental problems, and the studies at this objective may quite possibly serve to make commercial geomagnetic explorations much more successful.

Under this program we have need for a systematic repetition of absolute magnetic observations at a series of conveniently-situated base-stations the country over; we need more (detailed) regional magnetic surveying (tied to the base-station system) such as has been done by various governmental surveys and commercial organizations; and we need continuous-record magnetic observations in active seismic and volcanic areas.

Program 4

A program for the study of roles which have been played by geophysical, geochemical, geological, and cosmic-terrestrial forces and processes--Work under this program is aimed at a determination of additional data regarding: (a) The physical constitution of the Earth; (b) the chemico-physical and dynamic processes operative within the body of the Earth; and (c) the possible relation of recurrent rhythmic liberations of volatiles and fluxes at great depth--with a consequent production of deep-focus seismicity, renewal of mobility in the asthenosphere, and development of new regional cycles of volcanic, seismic, and orogenic activity.

The great scientific possibilities of such work have been indicated by Professor R. A. DALY'S notable paper "Meteorites and an Earth model" [Bull. Geol. Soc. Amer., March, 1943]. This and other studies by DALY and BUDDINGTON, and by the many collaborators and authors mentioned by DALY, seem to have set the stage for some most promising additional team-plays between the research-workers who have been studying the processes operative in the depths of the Earth and the active geoexplorers who have been working downward in the third dimension, by projection from quantitative data collected from surface and near-surface observations.

The prosecution of such a program will undoubtedly lead to all manner of interesting and useful discoveries, and it will also undoubtedly call for the collection of much more quantitative information on the physics and chemistry of different types of active volcanoes, on the physical-chemical behavior of complex mineralogical systems under varying scales of temperature and pressure--with and without the admixture of volatiles and natural solvents.

(Arrangements should be made to include in this program one unit of work to be undertaken in conjunction with the American Petroleum Institute's Geological Research Committee--this unit to consist of the progressive application of moderate hydrostatic pressures, at moderate temperatures, to "tar-belt" material which is suspected of being the parent-substance of petroleum.)

Program 5

A program for the further geophysical-geological study of continental margins, as a preliminary preparation for the resumption of extensive and intensive study of the structure, morphology, and composition of the sub-oceanic lithosphere--The importance of geophysical-geological study of this sort has been abundantly demonstrated, especially by work done along the east and west coasts of the United States under the sponsorship of the Geological Society of America, and along the coast of Great Britain under grant from the Royal Society of Great Britain. The opportunity and need for further work of this character along other continental borders was pointed out in a Symposium held at Richmond, Virginia, on December 27, 1938, under the joint auspices of the American Geophysical Union and of Sections D and E of the American Association for the Advancement of Science [Trans. Amer. Geophys. Union 1942, pp. 5-56].

If even a moderate amount of well-planned preliminary work can be carried forward currently in suitable Coastal-Plain areas, it should be possible to reinstitute comprehensive programs of

off-shore exploration as soon as hostilities cease--with the practical certainty that many important new facts regarding the oceanic areas will be continuously revealed thereafter, as suboceanic explorations progress.

Program 6

A program for a compilation study of quantitative data and "type-feature" illustrations of the Continental structural features and patterns such as are characteristically found in: (a) Unlithified sedimentary deposits; (b) lithified sedimentary deposits with considerable emphasis upon the evaporites (gypsum, rock-salt, etc.); (c) the less deformed metamorphics and plutonics of the outer part of the Basement Complex; and (d) the once deeply-buried parts of the Basement Complex--where these now lie revealed in consequence of uplift and erosion--An enormous volume of accurate, quantitative, and non-confidential information bearing on such a project now exists in the hands and files of oil-companies, mining companies, and geoexploratory organizations, and it is now possible to carry out very productive regional compilations and analyses of this information. The immediate consequence of such compilations should be a clear revelation of the structural types and structural patterns which are characteristic of different continental regions. And inasmuch as these same features commonly act as controls in the localization of oil-fields and ore-bodies, additional studies of the characteristic forms and patterns of these features might point to new regions as having promise for new strategic discoveries of minerals--which may be a matter of great practical importance in the post-war period, since the whole world will by then be suffering from an acute depletion of its proven deposits of oil and minerals.

As a part of this program, a project should be worked out looking toward an "engineering" study in field and laboratory of the compaction-characteristics and mechanical behavior of unlithified sedimentary materials. Researches made in the field by geologists working in the Mississippi Delta Area and in the whole Gulf Coast Region have been yielding very interesting quantitative data on the general geophysical-geological conditions prevailing there, and on the role being played by lithologic compaction in the development of the Gulf Coast's characteristic structural and sedimentary patterns. A study of similar features (though developed on a smaller scale) has been and is being made by the workers in the engineering field of "Foundations, Earth-structures, and soil-mechanics", and it seems certain that the establishment of a closer collaborative liaison between the various workers in this general field of Earth-science will speedily yield important and interesting results, especially since it is becoming more and more necessary to erect great engineering structures in areas of deep alluvial fill and when the construction and maintenance of strategic airports are matters of great and growing importance and interest.

Program 7

A program for collaboration of the American Geophysical Union in the establishment of summer training centers for students who are preparing for professional work in geoscience (both research and applied)--Necessities of war have already forced many transformations in educational patterns and procedures being used for the training of future geoscientists. The present hour presents a particularly favorable time for giving a careful consideration to the future research needs and opportunities in geoscience, to the ways in which good students can be drawn into these fields in balanced numbers, and to the possibilities of increasing the efficiency and professional adequacy of the instruction being given these young men.

This topic has for some time been one of rather acute interest, and even of concern to some of the larger mineral-industry companies as well as several of the mineral-industry scientific societies and educators, and the trend of thought seems to be toward the further development of Earth-science field-conferences to be held annually, at regular dates, and in type-areas (these conferences probably to be held under the sponsorship of various local geophysical and geological groups), to be open to qualified advanced students and research workers, both from American schools and laboratories and from similar institutions abroad.

If centers for such conferences can be established in a number of type regions within the United States, they can also be used during the rest of the summer field-season for the screen-testing and initial training of other students entering the early stages of professional geoscientific training.

APPENDIX I--SPECIAL COMMITTEE ON AUDIT

J. B. Kincer A. G. McNish, Chairman

Your Special Committee on Audit has made an examination of the accounts of the American Geophysical Union for the year ending December 31, 1942. It finds that the statement of the General Secretary is correct as given, namely, that the receipts of the Union during the calendar year, including balance as of January 1, 1942, are $12,651.76 and total disbursements are $5,870.41, leaving a balance of $6,781.35. This is covered by a bank balance of $6,778.35, when allowance is made for two checks outstanding as of December 31, 1942, in the amount of $127.50, and one check not then deposited in the amount of $3.00.

Your Committee has found that the records have been excellently kept, that all receipts and disbursements [see appended statement] are duly substantiated, and that the methods of handling the accounts are clear and efficient.

Statement of receipts and disbursements
January 1 through December 31, 1942

Receipts		
Cash balance, January 1, 1942, per audited accounts for 1941		$ 6,008.34
American Geophysical Union	$3,785.66	
Bowie Medal Fund	211.60	
Washington Assembly	1,876.08	
Special Fund	135.00	
Dues, 1940, 1941, 1942, and 1943		4,748.00
1940	$ 12.00	
1941	93.00	
1942	4,532.00	
1943	111.00	
National Research Council in payment of vouchers		102.43
Sales of Publications		1,627.01
Transactions	$409.41	
Reprints, Transactions of 1939	25.00	
Reprints, Transactions of 1941	355.75	
Reprints, Transactions of 1942	590.64	
Bibliography (including $198.70 from International Union of Geodesy and Geophysics)	232.61	
Reprints from Proceedings of International Association of Geodesy	13.60	
Miscellaneous		165.98
Sales, Special Exhibit maps	$ 25.25	
Contributions to Special Fund	102.00	
Donations to General Fund	4.00	
Reimbursement from C. S. Jarvis a/c changes in article in Transactions of 1942	10.00	
Reimbursement from International Commission of Snow a/c air-express charges advanced	9.80	
Reimbursement from University of Nevada a/c express charges on reprints	14.63	
Overpayments	.30	
Total receipts		$12,651.76
Disbursements		
Transactions of 1942		$1,634.41
Paper for master-copy	$ 17.76	
Part I	749.90	
Drafting and photography	$ 94.25	
Typing text including corrections and changes	152.50	
Typing tables	21.00	
Proof-reading	21.25	
Planographer, 1980 bound copies	460.90	
Part II	866.75	
Drafting and photography	$117.25	
Typing text including corrections and changes	531.88	
Typing tables	201.62	
Proof-reading	16.00	
Forwarded		$1,634.41

Disbursements--Concluded		Forwarded	$1,634.41
Mailing services, Part I, Transactions of 1942			14.58
Reprints, Part I, Transactions of 1942			204.98
Printing one set of reprints, Transactions of 1941			15.93
Clerical services, General Secretary's office			1,800.24
Expenses, Membership Committee			354.44
Clerical services	$145.26		
Printing	83.11		
Postage	126.07		
Expenses, Finance Committee			27.70
Expenses, Sections			5.93
Express, General Secretary's office			18.00
Air-express charges advanced a/c International Commission of Snow			9.80
Postage, General Secretary's office			506.18
Telephones and telegrams			3.85
Twenty-Third Annual Meeting expenses			419.13
Committee on Meetings	$ 45.72		
Preparing, printing, and mailing programs	84.21		
Registration cards	22.60		
General Assembly	141.72		
Lanterns and operators	112.00		
Miscellaneous	12.88		
Stationery and office supplies			250.63
List of members and officers, preparing and printing			177.86
Statutes and By-Laws, printing			21.56
Special Exhibit maps, printing			9.89
Bowie Medal, engraving			8.00
One Triner postal scale, 4-lb. capacity			16.20
Miscellaneous			8.79
Washington Assembly a/c Proceedings of International Association of Geodesy			362.31
Typing, including corrections and changes	$ 71.87		
Planographer, 1400 bound copies	133.23		
Reprints	21.64		
Printing errata slips	10.15		
Supplies for mailing	48.66		
Mailing services	66.67		
Postage	10.09		
Total disbursements			$5,870.41
Balance December 31, 1942			$6,781.35
Riggs National Bank		$6,778.35	
American Geophysical Union	$4,823.98		
Bowie Medal Fund	203.60		
Washington Assembly	1,513.77		
Special Fund	237.00		
Check not deposited, American Geophysical Union		3.00	$6,781.35

Outstanding bills receivable and payable
December 31, 1942

Bills receivable, American Geophysical Union			$ 914.92
Dues, 1939-1942, 7 members in occupied countries who have not been dropped	$ 39.00		
Dues, 1941 and 1942, 18 members at $6.00	108.00		
Dues, 1942, 88 members at $3.00	264.00	$411.00	
National Research Council allotment for fiscal year to June 30, 1943		397.57	
Publications		106.35	
Bibliographies	$ 10.40		
Reprints, 1939 Transactions	50.00		
Transactions	45.95		
Bills payable, American Geophysical Union			2,241.02
1942 Transactions		$1,548.70	
1942 Reprints		692.32	

Bills payable, Washington Assembly		$1,513.77
Reprints, I.U.G.G. and Associations (deducting free copies):		
Seismology (bill rendered)	$ 90.00	
Scientific Hydrology (allotment made by Executive Committee)	1,000.00	
Volcanology (allotment made by Executive Committee)	300.00	
Postage and services in mailing reprints	123.77	

Recapitulation

	A.G.U.	Bowie Medal Fund	Washington Assembly	Special Fund
Cash balances	$4,826.98	$203.60	$1,513.77	$237.00
Bills receivable	914.92	0.00	0.00	0.00
Total assets	$5,741.90	$203.60	$1,513.77	$237.00
Bills payable	2,241.02	0.00	1,513.77	0.00
Net assets	$3,500.88	$203.60	$ 0.00	$237.00

Equipment owned by American Geophysical Union

One 18-inch large primer Burroughs typewriter, serial No. 60A232450.	$190.80
One 10-inch elite Royal typewriter, serial No. KHM-2076351	100.31
Two 4-drawer, 5x8-inch steel filing cases (gift)	0.00
Two steel posture chairs	22.00
One Globe-Wernicke, 2-pedestal, flat-top steel desk, 60x34 inches.	49.18
Total cost of equipment	$362.29

APPENDIX J--REPORT OF SPECIAL COMMITTEE ON TIME-SIGNAL SERVICE

Perry Byerly, W. A. Lynch, P. Sollenberger, C. H. Swick, Daniel Linehan, J. B. Macelwane, H. T. Stetson, H. O. Wood

H. E. McComb, Chairman

Your Special Committee on Time-Signal Service finds, in general, that the United States Naval Observatory time-signals as broadcast by the Naval Communications Service and the standard-frequency broadcasts from the National Bureau of Standards have met the needs of field-parties engaged in astronomical, geodetic, magnetic, and seismological work during the past year. Special-signals have been furnished to astronomical field-parties of the United States Coast and Geodetic Survey in remote areas.

The Committee recommends that the agencies responsible for the time-signal services should be commended, by appropriate resolution [see p. 288], for furnishing satisfactory schedules during war-time conditions.

APPENDIX K--REPORT OF SPECIAL COMMITTEE ON COSMIC-TERRESTRIAL RELATIONSHIPS

C. F. Brooks, J. A. Fleming, E. O. Hulburt, W. T. Thom, Jr., H. H. Clayton, N. H. Heck, H. Landsberg, N. Wiener, J. H. Dellinger, J. F. Hellweg, J. Q. Stewart

H. T. Stetson, Chairman

It is gratifying that with so many of the personnel increasingly absorbed in scientific work for the war, so much has been accomplished that will materially contribute to the fundamental work of the Special Committee on Cosmic-Terrestrial Relationships.

It is obvious that work of such nature as is of immediate concern to the military cannot be discussed when such discussion would necessarily entail restricted information. Yet without the advantages of free interchange of ideas possible in time of peace the amount of restricted collaboration has been encouraging and your Committee can report with assurance that when the time comes for unhampered exchange of information it will be evident that many basic contributions have been made to the field of cosmic-terrestrial relationships of fundamental consequence not only to science but to National welfare. During the period consideration may be appropriately

given to such coordinated programs as can foster at a latter date International cooperation in a field where data to be most effectively used must be gathered on a world-wide scale.

The International Commission on Continental and Oceanic Structure of the International Union of Geodesy and Geophysics and the Special Committee of the American Geophysical Union on Geophysical and Geological Study of Continents have emphasized certain problems within their province whose solution can especially be helped through the cooperation of scientists in border-line fields somewhat overlapping some of the fundamental problems of your Special Committee on Cosmic-Terrestrial Relationships, and it is believed that a liaison of this International Commission and the Special Committees of the American Geophysical Union might aid in forming, even under present restricted conditions, International solidarity in such of these problems of science as are dependent upon the acquisition of data by more than one country.

Your Committee has offered its help when and as may be desirable in such problems, for example, as where gross crustal movements may be expected to result ultimately in measurable differences in geographic coordinates. A change in coordinates in the east-and-west direction involves interpretation of results that must rest upon the combined knowledge of geodesy, meteorology, and ionospherics--for the comparison of time-signals with high precision involves the variable conditions of radio communication.

Professor THOM has reported progress in the study of specific crustal deformations currently taking place. Such movements are of measurable magnitude and emphasize the need of an adequate time-scale in interpreting results from the geostructural viewpoint. Through the help of the International Commission it should be possible even under present difficulties to maintain a continuity of data the evaluation of which may have to await a more favorable opportunity. If the reception of time-signals from the friendly European and South American neighbors could be even somewhat extended, an important link in such fundamental studies would be preserved which can not later be recovered.

Certain members of your Special Committee, therefore, would like to recommend that the International Commission on Continental and Oceanic Structure take under careful consideration the possibility of greater immediate cooperation in restoring and continuing the daily recordings of time-signals between the Americas and with Great Britain even under the restrictions necessitated by the present world situation.

Reports received by the Chairman from nearly every member of your Special Committee have indicated that progress has been made but expediency prevents any detailed consideration either of the results or of the specific fields of investigation that may be of direct or indirect military significance. Only the most generalized information regarding some of this work can be included in this report.

Dr. BROOKS of the Blue Hill Meteorological Observatory reports that continuous records of total direct and indirect solar radiation on a horizontal surface and of the solar beam at normal instance have been continued during the past year and since 1932. On clear mornings when there was little variability of intensity, two pairs of screenings have been made with Schott filters OG_1 and RG_2.

A comprehensive study of filter-measurements from 1933 to 1940 has been made by EDMUND SCHULMAN and will be published as "Filter measurements of solar radiation at Blue Hill Meteorological Observatory" as Harvard Meteorological Studies No. 7. This will include tables of 1250 individual values of unscreened, red-screened, and yellow-screened measurements together with an estimate of their quality, the Ångstrom turpidity-coefficients and the synoptic air-mass at the time.

The Superintendent of the Naval Observatory reports that there has continued the regular transmission of time-signals although it has been necessary to reduce the number of daily transmissions on account of war conditions. A limited comparison of time-signals on high frequencies only has been maintained between Great Britain and the United States. The accumulation of solar-activity data has been continued but the discussion of this must be restricted.

With the approval of the Director of the United States Coast and Geodetic Survey, Captain HECK has furnished your Special Committee with the following report of the Survey in matters of important consideration in cosmic-terrestrial relationships:

"(1) In magnetic observations in South American Republics in cooperation with the governments concerned, special attention was given to repeating the measurements of the large diurnal variations in the region of the magnetic equator.

"(2) The earth-current observations that had been made for 12 years at the Tucson Magnetic Observatory in cooperation with the Carnegie Institution of Washington and the Bell Telephone Laboratories were discontinued on March 1, 1943, when the telephone-lines used became no longer available. Plans are being studied to resume the observations with much shorter lines. The cooperative observations of atmospheric electricity were continued at the Observatory.

"(3) Cosmic-ray recording apparatus was operated at the Cheltenham Magnetic Observatory, the records being sent to the Carnegie Institution of Washington for processing.

"(4) Periodic daily ionospheric observations at various radio frequencies were made throughout the year at San Juan, Puerto Rico, by Dr. G. W. KENRICK, in charge of a project of the Work Projects Administration sponsored by the United States Coast and Geodetic Survey. The data were forwarded to Dr. Dellinger of the National Bureau of Standards.

"(5) K-numbers for the five magnetic observatories, Puerto Rico, Honolulu, Sitka, Tucson, and Cheltenham were furnished the Department of Terrestrial Magnetism, Carnegie Institution of Washington."

While much of the work of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington has been in connection with the war, its Director, Dr. J. A. FLEMING, has been able to report much of interest in geomagnetic investigations and terrestrial electricity. A study has been made of world-wide distribution of magnetic anomalies and new world isoporic charts are in the process of construction. Large systematic errors in present geomagnetic charts have been found. The new charts should assist materially in providing new rates of sectional changes. Concerning the annual variation it has been found that one component is symmetrical about the equator with a minimum near the equinoxes and varies with the latitude. Another component is nearly sinusoidal in character with a period of one year, the minimum occurring at the winter solstice and the maximum at the summer solstice. The amplitude of the variation has been found to be twice as great during the year of sunspot-maximum as for years of sunspot-minimum.

Ionization-meters have been designed, constructed, and a preliminary investigation made of the rate of ionization at the Earth's surface due to the radioactive content of the Earth's crust. Investigations of atmospheric-electric phenomena at Watheroo and Huancayo have indicated that nuclei introduced into the atmosphere though terrestrial sources may extend throughout a stratum at least one km in height.

The continued investigation of cosmic rays has been carried on under the auspices of the Institution's Committee on the Coordination of Cosmic-Ray Investigations. In ionospheric investigations the Department has been in full cooperation with Governmental agencies.

The Department of Terrestrial Magnetism in collaboration with the University of Alaska has maintained important magnetic, ionospheric, and auroral observations and cooperative work has continued with surveys in Africa, Australia, New Zealand, Greenland, and elsewhere through the loan of instruments and supplies.

H. H. CLAYTON has continued his investigation of solar activity and certain apparent meteorological correlations. Some of his work now in progress is in connection with the Government war program and can not be discussed here.

Professor J. Q. STEWART has made progress in the study of recurrences in solar phenomena with apparently increasing evidence for a persistent cycle when allowance is made for phase-changes under certain characteristic conditions. Mathematical treatment of this will be published at a later time.

The Cosmic-Terrestrial Research Laboratory at Needham has continued its program of geophysical observations with major emphasis on investigations of immediate consequence to the war.

In the report of a year ago it was stated that arrangements had been completed for stationing at this Laboratory one of the new cosmic-ray counters for continuous recordings in a cooperative project with the University of Chicago, Massachusetts Institute of Technology, and the United States Weather Bureau. The apparatus was completed and installed in a separate shelter at Needham in May, 1943, and is now giving continuous records of counts in three regions of the cosmic-ray spectrum. Two stations have now been put into operation of those planned for nation-wide distribution.

The magnetic station established on the grounds of the Laboratory in 1940 was reoccupied by the United States Coast and Geodetic Survey in May, 1943, and careful determinations made of the principal magnetic elements preparatory to establishing recording apparatus at a later date.

In addition to the continuance of its observational program, it is the purpose of this Laboratory to cooperate with your Special Committee in bringing together significant data of interrelated fields that bear upon the whole subject of cosmic-terrestrial relationships. In turn your Special Committee solicits the cooperation of all the Sections of the Union and the other Special Committees in supplying information from their respective interests that may in any way contribute to this end.

The Chairman takes this occasion to thank the various members of the Committee for their effective cooperation under many difficulties due to the National emergency.

APPENDIX L--REPORT OF SPECIAL COMMITTEE ON FINANCE

K. C. Heald W. W. Horner G. W. Musgrave
Richard M. Field, Chairman

Your Special Committee on Finance deeply regrets that it does not have a more cheerful report at this time. We do not believe that the Union will be particularly interested in the results of our research regarding the difficulties of raising money for fundamental geophysics since Pearl Harbor, and the Chairman is not at all sure that he has done as well as he should--in fact, his conscience tells him that someone else could have done much better.

Undoubtedly the best work this year is that of the Committee on Membership and particularly those members of the different Sections of the Union who have been particularly responsible for the increase in membership. All of us who have received and voted on the frequent lists of new Members know the names of the sponsors, and, therefore, the high percentage of Washingtonians who have procured the new Members. I wish that this had been equally true of the non-Washington Members of the Union. Our membership is now approximately 1,800, and there is good reason to believe it will reach 2,100 or more before the end of 1943.

Our Special Committee on Finance has had it forcibly called to its attention by many Members of the Union that it should increase the annual dues to $5, and that membership (including the publications) is well worth this price. In his report last year, the Chairman of the Special Committee on Finance hoped to stimulate some rivalry between the Sections in the raising of a John A. Fleming Publication Fund. We have the William Bowie Medal in memory of one of the staunchest Members of the Union. What greater tribute could we pay--what greater evidence could we give--of our gratitude and appreciation of the outstanding services which JOHN A. FLEMING has rendered the Union than by all helping to raise a special publication fund in his name? So far, except for a few individuals, we have had no great response from the Sections, as such, with the exception of the Section of Hydrology. The contributions and pledges from the Members of the Union are somewhat less than $500. On April 14, 1943, J. E. CHURCH, President of the Section of Hydrology, informed the Chairman of your Special Committee on Finance that, at the meeting of the Executive Committee of the Section of Hydrology held at Washington on March 18, 1943, it was recommended that the Special Committee on Finance be enlarged to include at least one member from each Section of the Union, and that the representatives of Sections aid the Special Committee in the direct approach to the older members of the Union for contributions to the Special Publication Fund. I quote from the minutes of the meeting of March 18, 1943, of the Executive Committee of the Section of Hydrology as follows: "Support for an endowment known as the John A. Fleming Publication Fund will come from contributing organizations in proportion to the personal contributions from the members. Suggestions have been many that the annual dues be raised to $5. This may be desirable after the new Members have realized the value of the Union, but the opportunity for the older Members to make voluntary contribution of $1 or $2 each, even for one year, is at hand."

That the task set the Special Committee on Finance may be the better understood, there is appended [see Appendix M] a statement prepared by the Chairman of the Special Committee on Establishment of American Journal of Geophysics, which outlines the general plan and estimate of requirements.

After repeated consultation with the Executive Officers of the Union, the Chairman of your Special Committee on Finance forwarded a request to the Carnegie Corporation of New York for

$10,000 per year for three years, in order to convert our Transactions to the form of an American Journal of Geophysics (monthly or bimonthly) until the publication be entirely self-supporting through increased membership of the Union. This request was carefully prepared by two Members of the Union not on the Special Committee on Finance, and is an excellent summary of the responsibilities, growth, accomplishments, and present financial status of the Union. I suggest that, with only slight modification, this same statement would serve as an excellent pamphlet for distribution to the Members of the Union, especially in the light of the recommendations from the Section of Hydrology.

In a recent reply from the Carnegie Corporation of New York, it was stated that the Corporation had "not seen their way clear to make grants for support of periodicals such as Transactions, or for the establishment of new magazines such as you propose under the title, American Journal of Geophysics." The Chairman, however, has not taken this statement from the Carnegie Corporation as final, especially as he is convinced that the Corporation may very well reconsider the financial problems of our Union not merely in the purely technical terms of the "establishment of new magazines."

APPENDIX M--REPORT OF SPECIAL COMMITTEE ON ESTABLISHMENT OF AMERICAN JOURNAL OF GEOPHYSICS

L. H. Adams, V. Conrad, F. W. Lee, W. W. Rubey, C. F. Brooks, R. E. Horton, H. A. Marmer, C. H. Swick, J. A. Fleming, Chairman

The American Geophysical Union has to do with those theoretical or applied sciences relating to the Earth, its configuration, its structure, and the natural forces in operation upon or within it. Since inception in 1919, the Union has gradually developed so that now (over 2,000 Members in September 1943) it is the principal organization in the United States of America acting as a clearing house for new thoughts and ideas relating to geophysics. Its functions include the initiation and coordination of researches which depend upon International and National cooperation, and provision for their scientific discussion and publication.

The Union's efforts to secure additional funds are based on (1) increased membership, (2) voluntary contributions from Members of the Union, and (3) grants from endowed organizations. These are to make possible (a) the appointment as General Secretary of a well-qualified geophysicist to give his entire time to the work of the Union in order to realize fully the Union's great potentialities as a factor in geophysical progress and development in the United States and throughout the Western Hemisphere and, as proved in past experience, even in Europe, Australia, New Zealand, and Asia; (b) to effect a rearrangement of the Transactions of the Union so that they may become literally an American scientific journal of geophysics to include not only communications presented at annual and regional meetings of the Union, but also valuable papers communicated from time to time.

This proposal has been under consideration for some years and the original underlying ideas were published in our Transactions of 1935 [pp. 18-19]. It has been favorably considered by the Executive Committee of the Union and authority was given for the appointment of a Special Committee on Finance to realize the financial requirements. Roughly, these requirements involve a total fund of $30,000, in addition to dues from Members, over a three-year period to place the Union on a secure financial basis with a paid General Secretary and assistants.

It seems certain that after three years the Union and the proposed Journal will be so well established that, with an increase of the annual dues from $3 to $5, no further subsidy will be necessary.

A suitable man as General Secretary should have an initial rate of pay of around $4,000 per year; there should be at least two additional paid assistants at about $1,800 each per year besides the one paid clerical assistant (provided by the budget since June 1937); and a suitable moderate honorarium should be provided for each of eight associated editors to whom would be assigned the general oversight and recommendation for or against acceptance of papers submitted for publication in the fields of the Union's Sections. In addition, there are the necessary expenses of maintaining meetings, records of membership, distribution of publications, rental, communications, and general administration.

Through the most stringent economy and generous cooperation and gratuitous services of

Members and elected Officers of the Union, it has been possible gradually to accumulate a reserve which, by December 1943, will be about $5,000--that is, that amount will be free of obligation after the publication of the Transactions for 1943. Several years ago the Executive Committee authorized a proposal to establish a Special Publication Fund with the idea that individual Members of the Union would contribute a moderate total. This effort so far has not been very productive, most probably because there has been neither a systematic campaign nor extended canvassing for the needs among the entire membership. Despite this, the voluntary contributions, ranging in amount from $1 to $100, total already about $300. Rapidly changing economic conditions and the widespread development of geophysics--largely because of the good work of the Union since 1919 and particularly because of its meetings and published Transactions--make it imperative that we now take concerted and systematic steps to establish a secure status for the future. There is no doubt but that each Section can provide totals of around $500 or more for the Fund. An earnest effort is thus certain to ensure $5,000 to $6,000 more almost immediately and thus give a nucleus of around $10,000 to $12,000 for the needed expansion in the work and publications of the Union. With so substantial a showing of self-help and past performance, we may with all reason expect substantial aid from other interested sources. The Special Committee on Finance, with so good a past record and contributions from the Union itself, is certain to secure additional grants elsewhere which will make up the estimated required total of $30,000.

With such a foundation and a further increase in membership, which is quite apparently possible by the remarkable work in the past year of our Committee on Membership, financial security for future operations and our responsibilities to geophysics should be fully accomplished.

The fields of the Union are as important as any other of human endeavor, be it in applied engineering, chemical engineering, or other effort based on scientific progress. It appears, therefore, that in order not to lose the benefit of what has been accomplished through the hearty cooperation of so many individuals on what has been a penny-pinching procedure, we must realize the contemplated plan for an enlargement of the Union and the regular publication of an American scientific journal of geophysics.

That this plan is in no sense fantastic is evidenced fully by the Union's record in the past quarter-century which is briefly summarized as follows: During 1919 through 1931 funds required for functioning and publications of the Union were provided by the National Research Council. During these years the annual grants of the Council for the expenses of maintenance varied from $200 to $1,000, and the total additional amount provided by the Council in publishing some 1,250 pages of seven volumes of Transactions and one special report entitled "Survey of research problems in geophysics" was about $7,600. With the rapid growth and influence of the Union it was arranged that annual dues be contributed by each Member from 1932 ($2 from 1932 and $3 since 1937) and the annual grant from the Council was reduced to an average of $400. From 1932 through 1942 the total of annual dues was $30,337, sales of publications yielded $24,802, contributions for special purposes amounted to $7,597, and grants from the National Research Council aggregated $5,692--a grand total of $69,941. During the same interval the publication of some 26 volumes in 12 years of Transactions (7,967 pages in a format equivalent to 12,000 pages of the conventional printer's format), of five volumes (400 pages) of "Bibliography of Hydrology, United States of America", and of reprints cost $34,787, the cost of maintenance including a paid clerk from 1937 was $22,210, and the total of costs of necessary equipment and special-purpose expenditures was $4,628--a grand total of $61,625. Thus on April 24, 1943, there was a reserve of about $8,316 against future operations and publication of the Transactions of 1943.

This satisfactory performance is the result primarily of the economical methods of offset publication which, with the study of methods of preparing master-copy for direct reproduction, has reduced the total average cost per page for editions of 2,000 to less than one-half that of the conventional form of publication in editions of 1,000 only; indeed, on a strictly comparable basis of actual content of the page of our Transactions and editions of equal number, the total cost per page has been only one-quarter as much. Furthermore, our Transactions have been sent free of charge to each Member, to a large number of libraries for purposes of public reference, and to between 300 and 400 of our colleagues in other countries throughout the world.

This brings us to consideration of the Union's function in the International aspects of geophysics. We have found means to be represented by delegates at each of the seven triennial assemblies of that body, all of which, except the seventh in 1939, were held in European cities. The Seventh Triennial Assembly was held in Washington, D. C., through the efforts of the American Geophysical Union in cooperation with the Department of State. It was judged by our foreign colleagues as one of the most successful of the seven as regards attendance and scientific discussion. To complete this undertaking the American Geophysical Union found, in addition to its own funds,

some $18,327 to cover expenses of $17,127--over one-third was provided by the Members of the Union and the remainder by generous special grants from the United States Government, the National Research Council, the Geological Society of America, and the Carnegie Corporation in almost equal shares of $2,700, after refunds of $300 to each of the three last-named.

Surely, upon the record, the desired Special Fund is warranted and its realization in full seems assured.

APPENDIX N--REPORT OF SPECIAL COMMITTEE ON NATIONAL WELFARE AND RELATED FUNCTIONS

Miss L. A. Boyd	L. P. Eisenhart	J. P. Marble	A. K. Snelgrove
P. W. Bridgman	R. F. Griggs	K. F. Mather	H. T. Stetson
W. H. Bucher	H. D. Harradon	O. E. Meinzer	W. T. Thom, Jr.
E. G. Conklin	N. H. Heck	R. A. Millikan	T. G. Thompson
E. DeGolyer	J. B. Macelwane	F R. Moulton	F. E. Wright

R. M. Field, Chairman

Particular attention has been paid to the following subjects:

(1) The supply and demand for aerial photographs in research and education
(2) The classification and location of Latin-American students in the educational institutions of the United States
(3) The effect of scientific war research and education on non-military research and educational institutions

Aerial photographs--Aerial photographs are becoming increasingly important in all phases of geoscience which have to do both with war and with peace. As we all know, the war has been an immense stimulus to the production, improvement, and use of aerial photographs. In the case of war, these are essential not only to our ground-forces but also an important aid to aerial navigation. Near the end of this war there will be immense numbers of world-wide aerial photographs which will be of great value to geophysicists and to geologists. The cataloging, filing, and study of these photographs will be a tremendous task in itself, and some thought should be given immediately as to how this can be best accomplished, especially for the Western Hemisphere. We have already given some attention to the preparation of educational material for certain type geological areas in the United States and Canada. It appears that there are such type-areas illustrated by aerial mosaics and equivalent maps, both topographic and geologic. The problem has been to obtain the release of this material during the war. Since, however, the areas being selected are limited, widely dispersed, and not of any particular military significance, it is hoped that this essential material for teaching will be made available to all competent individuals and institutions for educational purposes.

Latin-American students--For some time your Special Committee has been particularly interested in the classification and location of technical students of Latin America in the educational and research institutions of the United States. Lately this interest has been extended to refugee students and educators and research-workers, particularly from China and Japan. Your Special Committee has been greatly aided in its inquiries by several organizations, among which we should like to mention particularly the Committee on Friendly Relations Among Foreign Students (SAMUEL J. MILLS, General Secretary) and the Coordinator of Inter-American Affairs. WILLFRED MAUCK, Adviser on Student Exchanges of the latter, has been most helpful. The Chairman called to the attention of Messrs. MILLS, MAUCK, and PARSONS (Secretary of the American Institute of Mining and Metallurgical Engineers) the growing desire of technical students of Latin America to meet each other while they were studying in the United States; also, that the available lists of these students did not sufficiently designate their separate fields of study. Mr. MAUCK has kindly kept the Special Committee informed as to the names, countries, departments of geoscience, and location of all Latin-American students as fast as such information was received by his office. The list is as yet by no means complete, but it covers 27 divisions of Earth-science, and includes students from Argentina, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, Guatemala, Honduras, Mexico, Nicaragua, Panama, Paraguay, Peru, and Venezuela. By far the larger number of these technical students seem to be coming from Mexico. For some reason or other, Brazil is not sending us as many technical students as several of the other Latin-American countries; but it may be gratifying to note that Venezuela is well represented. The majority of these students of Latin America are attending western colleges and technical institutions--the three outstanding are the Texas College of Mines, the Colorado School of Mines, and the University of Oklahoma. With the exception of the Massachusetts Institute

of Technology and Harvard University, relatively few Latin-American students are attending eastern institutions. Although the list is certainly not yet complete, it is probably sufficiently so to afford a fair sample analysis. It is also gratifying to note that the present list includes a relatively high percentage of Latin-American technical students who are studying applied geophysics and geology and geography. The Commission on Continental and Oceanic Structure of the International Union of Geodesy and Geophysics is considering the propriety and possible advantages of sending copies of its latest reports to those Latin-American students who are studying geophysics and geology in the United States and Canada. Would it be appropriate and advisable for the American Geophysical Union to open its associate membership to such students, especially if they were sponsored by their American instructors?

Fundamental research--Your Special Committee has necessarily been concerned with the effect of scientific war research on education in private or endowed non-military research and educational institutions. The Chairman would like to record here the particularly significant remarks recently published by one of its members, Dr. R. A. MILLIKAN, in one of our technical journals, and referred to in an editorial by the New York Times, under the title of "Science and war": "It is a terrific blunder to assume that war promotes science. The apparent stimulation of science by war lies in the hasty development and application of scientific discoveries which, under normal conditions, would have a more economical though slower development. We pay for this haste not only in extra pecuniary cost, but in the drying up of the source of further scientific development by the complete abandonment of fundamental, unmotivated (undictated) research. So much has been said and written during the last year by prominent chemists, physicists, engineers, and industrialists about the new scientific gadgets which will result from the war that the public is led to believe that science is concerned primarily with gadgets--even in times of peace." It is, therefore, particularly heartening to hear Dr. MILLIKAN'S voice heard in protest among so many of his distinguished colleagues. The purely mechanistic and monetary adaptations of scientific discoveries will, and should, have their proper influence on our educational institutions, but it will be a great mistake if "war needs" and "war economy" exhaust the possibilities of fundamental science itself. At the suggestion of certain members of your Special Committee, the Chairman addressed the following questions to the President of the United States for reference to the National Defense Research Committee under the Office of Scientific Research and Development:

(a) What is the dollar value in salaries and existing equipment utilized by existing scientific and educational institutions on a non-profit and non-loss basis in cooperation with the Federal Government for which Federal compensation is not directly received?
(b) What is the aggregate value of salaries and the estimated value of equipment of scientific and educational institutions for which compensation is being received?

It has since been agreed by the Bureau of the Budget, Executive Office of the President, that these questions are pertinent and are worth consideration, particularly in relation to post-war developments in education and research, but that the suggested type of "Bookkeeping" is not at present in use. Further research will eventually be needed.

APPENDIX O--REPORT OF SPECIAL COMMITTEE ON RESOLUTIONS

Earl Ingerson N. H. Heck
John Putnam Marble, Chairman

Nine resolutions, each previously adopted by vote of the Section or Committee concerned, were received by your Committee and, after consideration, were presented to the Business Session of the Union on Saturday, April 24, 1943. These were sponsored by the following Section or Committee according to the numbers given them: (1) Committee on the Twenty-Fourth Annual Meeting; (2) Section of Geodesy; (3) Sections of Geodesy and Seismology; (4,5) Section of Meteorology; (6,7,8) Section of Seismology; (9) Section of Terrestrial Magnetism and Electricity.

The texts of the resolutions and action taken by the Union at the Business Session are given on pages 286-288.

The present method of handling and presenting resolutions is by no means satisfactory. The Committee on Resolutions does not have adequate time to consider, compare, collate, and combine the various resolutions handed to it by the Secretaries of the Sections and others; furthermore, the Union, as a whole, has no adequate opportunity for discussion before taking action.

It is respectfully suggested that the question of a modification of the present procedure be

placed on the agenda of a meeting of the Executive Committee in time to have such modification, if approved, take effect at the next Annual Meeting of the Union.

APPENDIX P--REPORT OF SPECIAL COMMITTEE ON NOMINATIONS

O. W. Swainson E. G. Zies
G. W. Musgrave, Chairman

The Special Committee on Nominations is unanimously of the opinion that there is but one person to be proposed for the important office of General Secretary at this time.

These are critical times. The Nation is at war and many of our members--and particularly our General Secretary--are devoting long hours to matters of National importance. The Union is in a transition-stage with anticipations that an adequately financed permanent organization may take form in the near future. The duties connected with the office of General Secretary at present are burdensome to an extreme degree.

Your Special Committee believes it impossible even to consider a change of General Secretary, but it is convinced the burden of the office should be lessened.

Therefore, it recommends unanimously (1) the election of Dr. JOHN A. FLEMING as General Secretary, and (2) that the Special Committee on Finance take steps to provide early relief of the excessive load now carried and which includes especially the editing and seeing through publication of the entire Transactions.

APPENDIX Q-a--MINUTES OF THE ANNUAL MEETING OF 1943, SECTION OF GEODESY, AMERICAN GEOPHYSICAL UNION

The Annual Meeting was held in Room 202, Hall of Government, George Washington University, 21st and G Streets, Northwest, April 24, 1943. The meeting was called to order by the President, R. M. WILSON, at 9:20 o'clock.

Since the minutes of the Twenty-Third Annual Meeting held April 4, 1942, had been printed and distributed to the Members, and since no corrections had been received, the minutes were declared approved as printed and circulated.

The President called attention to the large increase in membership of the Section and called on J. A. DUERKSEN, the representative of the Section on the Committee on Membership, for a statement in regard to the activities of that Committee.

The President requested everyone attending the meeting of the Section of Geodesy to register at the booth in the entrance lobby.

A report of the Nominating Committee (H. W. HEMPLE, Chairman, L. V. JUDSON, and J. E. WILLIS) was given by Mr. Hemple. J. A. DUERKSEN was nominated for Secretary of the Section for a three-year term beginning July 1, 1943. No nominations were made from the floor and Mr. Duerksen was unanimously elected.

Since no member of the Committee on Resolutions was present, the President called for action on the Resolution as printed in the program for the meeting [see p. 286]. Upon motion, the Resolution was approved following discussion by Messrs. Garner, Mitchell, Hemple, Hain, Randall, Howe, Gish, Thom, Rappleye, Hough, and Lambert.

W. D. LAMBERT then presented the following motion and statement in support thereof:

Motion--I move that a Committee of the Section of Geodesy be appointed to consider the feasibility of establishing an International Journal of Geodesy, the Committee to report from time to time to the Executive Committee of the Section and to the next Annual Meeting of the Section.

Statement in support of the above motion--There seems to be a real need for an International Journal of Geodesy. The Bulletin géodésique, under the able editorship of General PERRIER, served a very useful purpose. No word has come from him for about a year. The physical misery that now prevails in Europe and that will still prevail to some extent for years to come, the enormous confusion over property-rights due to outright seizure and to forced sale, the unsettled

political conditions and the legacy of hatred that the war will leave all conspire to make it unlikely that the International Association of Geodesy will be able, within the foreseeable future, to resume operations on anything like the old footing. Of course, if and when the International Association of Geodesy shall be in a position to resume the publication of the Bulletin géodésique, or its successor, any journal that might have come into being as a result of this Resolution would naturally merge with the Journal of the International Association, unless it should then appear that there was room for two similar journals.

There were two other publications that served to some extent as journals of geodesy, but they were not international. They were "house-organs", so to speak, of the United States Coast and Geodetic Survey, namely, the Geodetic Letter and the Field Engineers' Bulletin. Both have been suspended for good and sufficient reasons but their disappearance leaves a vacancy.

The Empire Survey Review still carries on. Under the editorship of the late Captain McCAW, whom it was a privilege to know, it was a most interesting and valuable journal. And under the editorship of his successor, Captain CLENDINNING, it will undoubtedly continue to be interesting and valuable. But it is not an International Journal, except in so far as the British Commonwealth of Nations is International, and it covers only surveying, not the whole of geodesy.

In view of this, there seems to be room for a Journal of Geodesy, especially if the countries to the south of us take up geodetic work in their respective territories. This is an almost virgin field for geodetic operations, and for this very reason many interesting and important geodetic problems are likely to arise for the discussion of which a journal will be especially useful.

In dealing with the International phases of the question the proposed Committee will naturally act in cooperation with and with the approval of the various organizations that deal with the International organization of science, such as the American Geophysical Union, the National Research Council, and the proper officials of the State Department. It is with this understanding that the motion for the appointment of the Committee is made.

After discussion by Messrs. Mitchell, Randall, Hain, and Hough, the motion was passed.

The Section then proceeded to hear and discuss papers on the scientific program which appear on pages 31-49. After the meeting a paper entitled "Report of the geographical and topographical activities in Mexico during the year 1942" was received from MANUEL MEDINA. This paper is printed in these Transactions [see pp. 49-53].

The attendance was about 75 [see Appendix A].

The meeting adjourned at 12:30 o'clock.

WALTER D. SUTCLIFFE, Secretary

APPENDIX Q-b--MINUTES OF THE ANNUAL MEETING OF 1943, SECTION OF SEISMOLOGY, AMERICAN GEOPHYSICAL UNION

The Annual Meeting was called to order by the President, H. E. McCOMB, at 9:25 o'clock, April 24, 1943, in the Hall of Government, George Washington University, Washington, D. C. [For attendance, see Appendix A.]

The minutes of the previous meeting having been published and no objections or corrections received, the President declared them approved.

The President appointed a Committee on Resolutions consisting of FRANK NEUMANN (Chairman), F. W. SOHON, S.J., and A. K. LUDY. The Committee reported three Resolutions: On time-signals; on post-war employment of geophysicists; and on seismological investigation of the American portion of the circumpacific belt. These resolutions were adopted by the Section and transmitted to the Committee on Resolutions of the Union. [See pp. 287-288 for the Resolutions as adopted by the Union.]

The Secretary announced the appointment of O. W. SWAINSON to represent the Section at a conference on continental and oceanic structure at the General Assembly of the Union on the afternoon of April 24, 1943.

R. R. BODLE reported briefly on the work of the Committee on Membership of the Union, to which he had been appointed to represent the Section of Seismology.

There being no further business, the Section proceeded to the scientific papers [reported in these Transactions, pp. 57-96].

The meeting was adjourned at 11:50 o'clock.

ARCHIE BLAKE, Secretary

APPENDIX Q-c--MINUTES OF THE ANNUAL MEETING OF 1943, SECTION OF METEOROLOGY, AMERICAN GEOPHYSICAL UNION

The Twenty-Fourth Annual Meeting of the Section of Meteorology was held April 23, 1943, in two sessions, from 9:15 to 12:00 o'clock, President THORNTHWAITE presiding, and from 14:15 to 17:35 o'clock, Ex-President WEIGHTMAN presiding in the absence of Vice-President ROSSBY, in Room 101, Hall of Government, George Washington University. About 200 members and guests were present. [For attendance, see Appendix A.]

The reading of the minutes of the previous meeting was dispensed with as they had already been published in the Transactions of 1942, and no corrections or additions had been received.

C. F. BROOKS called attention to the inauguration in the January 1943 number of the Bulletin of the American Meteorological Society of a Latin-American Section in which articles written in Spanish will be published.

G. W. MUSGRAVE, Chairman of the Committee on Membership, called attention to the excellent work of the Section in connection with the effort to increase the membership of the Union and indicated ways in which additional Members may be secured.

R. H. WEIGHTMAN was appointed as a Committee of one to receive any Resolutions that might be proposed. Two Resolutions were presented which were transmitted to the Committee on Resolutions of the Union [see pp. 287].

As a result of deliberations extending over a two-year period, President THORNTHWAITE has appointed a "Research Committee on Physical Climatology" under the chairmanship of HELMUT LANDSBERG; other members of the Committee are ALFONSO CONTRERAS ARIAS, PHIL E. CHURCH, W. C. JACOBS, J. B. LEIGHLY, A. E. PARR, F. W. REICHELDERFER, A. K. SHOWALTER, R. G. STONE, C. W. THORNTHWAITE, and H. G. WILM.

The scientific program consisted of 16 papers, three of which were read by title. They are printed in whole or in abstract on pages 99-214 of these Transactions.

H. D. HARRADON, Secretary

APPENDIX Q-d--MINUTES OF THE ANNUAL MEETING OF 1943, SECTION OF TERRESTRIAL MAGNETISM AND ELECTRICITY, AMERICAN GEOPHYSICAL UNION

The Twenty-Fourth Annual Meeting of the Section of Terrestrial Magnetism and Electricity was held in Room 203, Hall of Government, George Washington University, April 23, 1943. The meeting was called to order by President E. A. ECKHARDT at 14:20 o'clock.

The reading of the minutes of the last meeting was dispensed with, since they have been published in the Transactions of 1942. No corrections having been received, they were declared approved as printed.

O. H. GISH presented a Resolution regarding the American Geophysical Union's participation in war-to-peace transition planning. Following some discussion, the Resolution as presented was approved by the Section and transmitted to the Committee on Resolutions of the Union for adoption by the Union [see p. 288].

The following report was presented by Dr. H. H. HOWE, Chairman of the Committee on Units, appointed as a consequence of action taken at the last Annual Meeting:

(1) In view of the lateness with which the Committee was organized, it was impossible to consider fully all questions which should come before it. It is therefore requested that the life of the Committee be extended until the next meeting.

(2) There is confusion with regard to the unit of resistivity, as, for example, in geophysical measurements of earth-resistivity. We condemn such expressions as "ohms per cubic centimeter" and "ohms per cubic meter" as dimensionally incorrect. "Ohm-centimeter" and "ohm-meter" are dimensionally correct. Since the latter is of more convenient size for earth-resistivity, we recommend that a unit of that size be used. However, the phrase "ohm-meter" might be mistaken for the name of an instrument, especially in oral discussion. Therefore, we recommend that the unit of earth-resistivity be called the "meter-ohm", written with a hyphen.

(3) It seems to be general practice among physicists and electrical engineers to use "gauss" as the unit of flux-density and "oersted" as the unit of magnetic intensity (or magnetic force). It is only among some geomagneticians that "gauss" is used as a unit of intensity. We recommend that geomagneticians follow the general practice, and reserve "gauss" for flux-density only.

For measurements in air, however, the flux-density in gauss is numerically equal to the intensity in oersteds, within practical limits. Therefore, if either quantity is measured, one knows immediately the value of the other quantity. Thus, if H is measured with a magnetometer as 0.18197 oersted, we know at once that the horizontal flux-density is 0.18197 gauss. Therefore, either of the following expressions is permissible: "The horizontal intensity was found to be 0.18197 oersted" or "The horizontal flux-density was found to be 0.18197 gauss." But the following is incorrect and should be avoided: "The horizontal intensity was found to be 0.18197 gauss."

In accepting the report, the Section acted on paragraph (1), and paragraphs (2) and (3) as two parts. It was moved, seconded, and approved to extend the life of the present Committee as it now exists to the next meeting of the Section. A motion to approve the second portion [paragraphs (2) and (3)] was lost on the grounds that further study of the problem by the Committee with a subsequent study of their report by the Section was necessary before a satisfactory decision could be made.

An excerpt from the report of the Committee on Membership of the Union was presented by H. F. JOHNSTON to the effect that the number of members of the Union affiliated with the Section of Terrestrial Magnetism and Electricity had increased from 283 a year ago to 382 at present.

There being no further business, the Section proceeded to the scientific program and the papers published in these Transactions were presented [see pp. 217-234].

The first paper entitled "The study of the early history of terrestrial magnetism" by H. D. HARRADON was read by E. H. VESTINE. The progress-reports of the United States Coast and Geodetic Survey and the Department of Terrestrial Magnetism, Carnegie Institution of Washington, by Commander O. W. SWAINSON and Dr. J. A. FLEMING, respectively, were read by title.

As President E. A. ECKHARDT had to leave prior to the conclusion of the meeting because of urgent war duties, Vice-President H. F. JOHNSTON assumed the chair during the presentation of the scientific papers.

The meeting was adjourned at 17:00 o'clock.

J. W. JOYCE, Secretary

APPENDIX Q-e-MINUTES OF THE ANNUAL MEETING OF 1943 SECTION OF OCEANOGRAPHY, AMERICAN GEOPHYSICAL UNION

The Annual Meeting of the Section of Oceanography was held in Room 202, Hall of Government, George Washington University, April 23, 1943. In the absence of the officers, who were out of town, the meeting was called to order by L. P. DISNEY at 9:15 o'clock. Forty Members and guests were in attendance [see Appendix A].

The minutes of the previous Annual Meeting were approved as published in the Transactions of 1942.

A communication was read from the Chairman, Committee on Membership, calling attention to the membership drive now in progress.

There being no further business, the Section proceeded to the scientific program. The papers are printed in these Transactions on pages 237-247.

The paper by Admiral WAESCHE was read by Commander N. G. RICKETTS. The Scripps Institution of Oceanography was represented by Lieutenant R. R. REVELLE, who gave a summary of

the paper submitted by Dr. SVERDRUP. Admiral COLBERT'S paper was read by title and the paper by Dr. MEARS was read in abstract by the Secretary.

Following the presentation of the papers, Dr. R. M. FIELD suggested the formation of some organization to correlate and carry on the numerous oceanographic research-projects now being conducted by various organizations in the prosecution of the war.

The meeting was adjourned at 10:30 o'clock.

L. P. DISNEY, Acting Secretary

APPENDIX Q-f--MINUTES OF THE ANNUAL MEETING OF 1943, SECTION OF VOLCANOLOGY, AMERICAN GEOPHYSICAL UNION

The Annual Meeting of the Section of Volcanology was called to order, in the absence of President A. F. BUDDINGTON, by Vice-President J. F. SCHAIRER at 9:25 o'clock in Room 203, Hall of Government, George Washington University, Washington, D. C. The attendance was about 50 [see Appendix A].

The reading of the minutes of the previous meeting was dispensed with, as the minutes had been published in the Transactions of 1942.

The Secretary reminded the Members that many well-qualified geologists do not realize that the fields of interest of the Section of Volcanology cover petrology and the relation of ore-deposits to igneous activity, and requested that Members offer the advantages of membership in the Union to any such geologists of their acquaintance.

The scientific papers were presented as published in these Transactions [see pp. 251-268]. OSBORNE'S paper was discussed by Koschmann, Schairer, and Fleischer. KENNEDY'S first paper was discussed by Schairer, Ingerson, Wells, and Fleischer and the author was complimented on the stand taken on the relation of his experimental results to theories of the origin of ore-deposits. SCHAIRER gave a clear explanation of the background of the silicate-melt experiments and of the meaning and interpretation of the diagrams used in his paper. GLASS' paper was discussed by Robinson, Ross, Walton, and Vhay. KENNEDY'S second paper provoked much stimulating discussion and more than a dozen commented on the paper and its theoretical aspects, including Walton, Osborne, Ingerson, Fleischer, Field, Flint, Goddard, Van Alstine, Davis, Schairer, Ross, and Wells.

After the regular program the Secretary read a very interesting letter from DONALD E. WHITE describing the eruption of the volcano at Paricutin, Michoacan, Mexico, which first appeared in February, 1943; also a number of good kodachrome pictures of the eruption taken by PARKER TRASK were shown; the letter and pictures were made available to the Section through the courtesy of D. F. HEWETT.

The meeting adjourned at 12:30 o'clock.

JOHN S. VHAY, Secretary

APPENDIX Q-g--MINUTES OF THE ANNUAL MEETING OF 1943, SECTION OF HYDROLOGY, AMERICAN GEOPHYSICAL UNION

(The more detailed minutes will appear in Part II of these Transactions, which will cover the papers and reports presented before the Section of Hydrology.)

The Section of Hydrology held four sessions in the Hall of Government, George Washington University, on April 23 and 24.

The first session was called to order at 9:30 o'clock, April 23, by Vice-President STRAUB. Five papers and reports of four Research-Committees with discussions were presented. Three papers and reports of two Research-Committees were presented by title. The session adjourned at 12:40 o'clock.

The second session was called to order at 14:00 o'clock, April 23, by Vice-President STRAUB introducing Past President GROVER, who acted as Chairman for the session. Four papers and

reports of two Research-Committees with discussions were presented. Five papers and the reports of one Research-Committee were presented by title. O. E. MEINZER reported on the ground-water activities of the Water-Resources Branch of the United States Geological Survey. The session adjourned at 17:45 o'clock.

The third session was called to order at 9:15 o'clock, April 24, by Vice-President STRAUB introducing Past President SHERMAN, who acted as Chairman for the session. Eleven papers and the report of one Research-Committee with discussions were presented. Five papers and the report of one Research-Committee were presented by title. WALDO E. SMITH discussed the activities of the Committee on Membership of the Union. J. J. DOLAND made brief remarks concerning the summer meeting of the American Society of Civil Engineers at Los Angeles. The session adjourned at 12:49 o'clock.

W. G. HOYT, Acting Secretary

The fourth session, a round-table discussion of the papers and reports presented during the previous sessions, was called to order at 14:00 o'clock, April 24, by W. G. HOYT, Chairman. The paper on "The flood-hydrograph and valley-storage" by H. N. TURNER, and the paper on "On the plotting of flood-frequencies" by E. J. GUMBEL, were discussed by Clark, Gumbel, Hertzler, Krimgold, Langbein, Merriam, Snyder, and others. R. A. HERTZLER, Chairman of the Committee on Program, discussed the rules of the Section for presentation of papers and requested that abstracts of all papers be prepared in accordance with these rules. C. E. JACOB elaborated on his paper on "Correlation of ground-water levels and precipitation on Long Island, New York."

A general discussion on ground-water phenomena followed. C. F. MERRIAM explained the studies in the Susquehanna River Basin on the relation between ground-water and runoff. C. F. IZZARD elaborated on his paper on "Analysis of runoff resulting from simulated rainfall on a paved plot." The paper was discussed by L. G. STRAUB, who presented his observations of flow-conditions and unusual hydraulic phenomena, especially regarding types of flow at shallow depths. The session adjourned at 17:10 o'clock.

R. A. HERTZLER, Acting Secretary

APPENDIX Q-h--MINUTES OF THE ANNUAL MEETING OF 1943 SECTION OF TECTONOPHYSICS, AMERICAN GEOPHYSICAL UNION

The Annual Meeting of the Section of Tectonophysics of the American Geophysical Union was held in Room 202, Hall of Government, George Washington University, on April 23, 1943. The meeting was called to order by President L. H. ADAMS at 14:19 o'clock. The minutes of the previous Annual Meeting were approved as printed.

JOE WEBB PEOPLES, Chairman of the Nominating Committee, presented the following nominations for officers to serve for the period 1943-1946: For President, ERNST CLOOS; for Vice-PRESIDENT, L. L. NETTLETON; for Secretary, M. K. HUBBERT. It was moved and seconded that the nominations be declared closed and that the Secretary be instructed to cast a unanimous ballot for the nominees. The motion was carried and the President declared the nominees elected.

The President and Secretary each urged those presenting papers to have the manuscripts in the Secretary's hands as soon as possible after the meeting to facilitate publication of the Transactions [see pp. 271-282].

There were some 47 Members and guests in attendance [for registered attendance see Appendix A].

EARL INGERSON, Secretary

ERRATA

TRANSACTIONS OF 1942

Page 282--In view of possible misunderstanding, the following copy for Figure 1 is to replace that originally published in the article "The interdiurnal variability of temperature on Mount Washington" by V. Conrad (pp. 279-283).

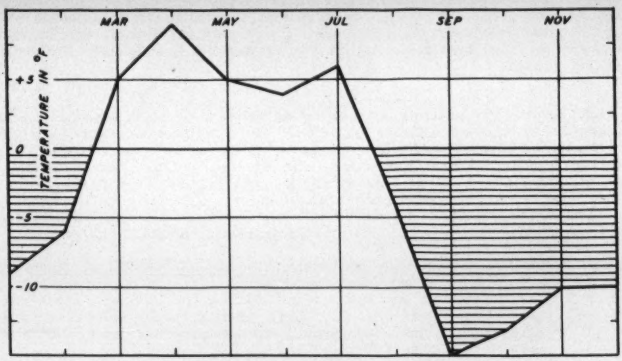


Fig. 1--Temperature-balance computed from coolings and warmings (5 a.m.) on Mount Washington in an average year

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AMERICAN GEOPHYSICAL UNION
ADDENDUM TO PART III, TRANSACTIONS OF 1943

ADDITIONAL DISCUSSIONS AT CORVALLIS MEETING

(Lost in files of Editorial Committee of the Section of Hydrology and not submitted by that Committee until after completion of Part III)

Paper on "Stream-flow forecasting by pattern-behavior" by Rolla H. Wahle [Trans. Amer. Geophys. Union, Part III, pp. 13-28, 1943].

ROLLA H. WAHLE (closure)--As to consideration of the method on streams principally rain-fed, and trial where snow is not a large factor, I may say this is the first time it has been tried anywhere, but since starting work on this about two years and a half ago, I understand that some other gentlemen have done work along this same line. The only stream where we carried on such work is the Columbia.

As regards success of the method on account of the presence of snow, I regard what Mr. McLAUGHLIN had to say about snow-measuring as extremely interesting. I know that it is, of course, of great value, but I am not sufficiently acquainted with the methods, or the results up to the present time, to have any direct proof. I hope to have before too long and then I may be able to answer.

Our records indicate a direct connection between the first six months and the second. There might be one phase of runoff-factors creating runoff in one period, and in a similar period it would be another phase of these factors that would create the runoff. A certain runoff during the initial six-month period indicates a similar balance of flow-factors that entered into it. One year it might be a rain that would bring a peak, another time a lack of rain would make flood-indications less ominous. I would think, by my studies up to the present time, that the first six-month flow is indicative of the last six-month-flow in many instances. There are probably many departures from pattern-groups, and if we had a record of the river for several hundred years we might determine departures.

Paper on "Some accomplishments in snow-surveying" by W. W. McLaughlin [Trans. Amer. Geophys. Union, Part III, pp. 38-43, 1943].

ASHTON CODD (Hydrologic Engineer, United States Weather Bureau Regional Office, Seattle, Washington)--Mr. McLAUGHLIN has mentioned many factors that enter into the complex problem of river-forecasting from snow-fed streams. In the day-to-day river-forecasting of rivers that rise in basins, which are partially or totally covered by snow, we find depth, water-content, and density do not give a complete picture of how much water will be released to runoff during a specific period of time. The quality of snow has a great deal to do with this particular problem and may be used as an index to snow-melt. Messrs. MERRILL BERNARD, WALTER T. WILSON, and PHILLIP LIGHT of the Weather Bureau Hydrometeorological Section in Washington, D. C , have presented some well-founded procedures and theories for coping with the snow-melt problem.

We in the Northwest are planning on carrying those procedures into the field for an actual trial and endeavor to apply the snow-quality measurements to river-forecasting. The snow-line elevation will also be observed to give a basis for computing that portion of the basin contributing to runoff or that area between the elevation of the snow-line and the elevation of the isotherm for 32°F.

Referring to Mr. CANFIELD'S question, the quality of snow may be defined as the ratio of the heat of melting of snow to the heat of fusion of pure ice. In a snow-pack there is a certain amount of free water. As soon as the snow melts, this water is liberated to runoff without requiring additional heat to change it into a liquid state as is the case of the ice-particles of the snow-pack. For example, snow of 60 per cent ice and 40 per cent water has a quality of 60 per cent and a heat of melting of $0.60 \times 80 = 48$ cal/gr or $0.60 \times 144 = 86.4$ BTU/lb. The factor to be determined is the heat of melting by using a calorimeter.

JAMES C. MARR (Boise, Idaho)--An Army Air Corps crew which crashed in the wilds of central

Idaho last winter reached a snow-survey shelter-cabin with its beds and stores of food and fuel after almost superhuman endurance during several days' travel through deep snow, and were saved at some expense to snow-survey facilities. The food was padlocked in a room in the basement and could have been reached by breaking the lock. The weary aviators, however, chose the more difficult and destructive procedure of ripping up the floor of the cabin.

Snow-surveys made during the middle of March in some sections and of April in others would be desirable. Also a measurement during mid-February would be useful during years of light falls of snow. I believe we should plan to enlarge the snow-survey program in this manner when it becomes possible to do so.

Paper on "Precipitation-runoff relationships as a basis for water-supply forecasting" by George D. Clyde and R. A. Work [Trans. Amer. Geophys. Union, Part III, pp. 43-55, 1943].

J. E. CHURCH (Nevada Agricultural Experiment Station, Reno, Nevada)--May I give you statistics for the present year at Soda Springs, at the summit of the Sierra? It was one of those many survey points at which we try to determine the runoff of the streams both east and west from this watershed. The precipitation there from November through March was 141.8 per cent of normal (a bumper year if it had been cold) but the snow-cover at the end of that period was only 98.2 per cent of normal on April 1 and snow was scant at lower elevations.

The people were afraid they would have a dry season because they had no snow down where they had seen it before, and the snow-cover at the low level was so small in amount that the snow-line was very, very high. And the snow was so extremely dense that the season was advanced, according to the old timers "a full month." Corporal WILLIAMS was so in hopes that we might see one of those "bumper" years while he was stationed in the Sierra. Only rains and melting prevented.

Likewise, in the Humboldt Basin during the same season (1942-43) the precipitation for November to February was 137.6 per cent of normal but the snow-cover on March 1 was 91.5 per cent of the normal of March 1 and at low levels only 42.1 per cent. But the forecast based on the highest water-table of record was a probable runoff during March to July of 185 per cent. On June 15 the runoff had already attained 168 per cent of normal. The effect of the high precipitation is clouded by the water-table. In the Sierra the runoff has usually corresponded with the snow-cover.

Unfortunately the superabundance of water in the precipitation has prevented the comparison of records of precipitation-gages with those of snow-surveys as Mr. ALTER intended. A winter-long comparison of ten precipitation-gages and recorders at Soda Springs revealed a high degree of accuracy of snow-catch that should compare favorably with that of snow-surveying. Both methods are necessary and mutually supplementary. One determines the winter gross assets in snow and water, the other the net assets of the remnant snow-cover. The latter, because of its quantity and continuity of melting, strongly influences the stream-flow.

Paper on "Forecasting runoff for power from relatively low-level areas" by Harry Olsen and E. B. Price [Trans. Amer. Geophys. Union, Part III, pp. 55-62, 1943].

J. E. CHURCH (Nevada Agricultural Experiment Station, Reno, Nevada)--Is not the runoff of the previous season or series of seasons given considerable weight in choosing the modifying factor applied by the authors to their data of snow and precipitation when forecasting the probable runoff of the current season? It is one of the steadying factors in the lava-watersheds, such as the Klamath and Pit, that have a hold-over from one season to the next.

In granite or even alluvial watersheds, as the Kern and Humboldt of Nevada, the basin may drain out to a minimum of 3.1 or even 0.8 per cent of the annual normal in September while the lava-beds may maintain a minimum of 4.1 per cent. Or, expressed in terms of the major flow during March to July or April to July due primarily to snow-melt, the flow of the Klamath will be only 53.9 or 42.0 per cent of the annual as compared with the flow of 67.5 or 61.4 per cent in the Kern and 83.2 or 71.2 per cent in the Humboldt.

The lack of crest or evenness of monthly flow in the Klamath as compared with the others is shown in Table 1.

Table 1--Monthly percentage of normal runoff in varying types of watersheds

Month	Alluvial soil Humboldt (Nevada) Palisade	Granite soil Upper Kern (Kernville)	Lava Klamath (Spencer Bridge)
	pct	pct	pct
October	1.7	3.3	5.0
November	2.2	2.8	6.0
December	1.9	2.8	7.8
January	2.6	3.9	9.1
February	3.8	3.6	9.4
March	12.0	6.1	11.9
April	19.0	10.1	13.3
May	20.0	17.3	12.4
June	23.5	22.4	9.5
July	8.7	11.6	6.8
August	1.5	5.3	4.6
September	0.8	3.1	4.1
March to July	83.2	67.5	53.9
April to July	71.2	61.4	42.0

In the three watersheds, the alluvial seems least capable of accumulating and distributing its flow, yet through a series of three years, its water-table has been built up until the soil has diverted sufficient melt-water into the stream-channel to double the flow based on the snow-cover during March to July. A snow-cover of 91.5 per cent of the normal on March 1 is producing a runoff that has already (June 15, 1943) attained 168 per cent of normal and is forecasted at probably 185 per cent.

It seems probable also that the lava-storage of the Klamath Basin may be built up or diminished sufficiently by the fluctuation of the snow-cover or precipitation over a series of years to affect the seasonal flow. This phenomenon is steadier and longer continued than the priming of the soil by autumn rains.

A project akin to forecasting on the Klamath is the relationship between the snow-cover on Charleston Mountain in southern Nevada and the fluctuation in the artesian flow at its base.

ASHTON CODD (Hydrologic Engineer, United States Weather Bureau Regional Office, Seattle, Washington)--Messrs. PRICE and OLSEN have a very unique scheme with which to forecast the stream-flow in the upper Klamath River. With the data they have collected, it would seem that a definite correlation between the runoff-factor and antecedent conditions should exist, especially where they have computed the runoff-factor for past seasons and compared it with their estimated factor. A graph plotted with runoff against precipitation for October to December, or some combination of factors, may prove very helpful.

Paper on "A simple procedure for the day-to-day forecasting of runoff from snow-melt" by Ray K. Linsley, Jr. [Trans. Amer. Geophys. Union, Part III, pp. 62-67, 1943.]

ASHTON CODD (Hydrologic Engineer, United States Weather Bureau Regional Office, Seattle, Washington)--Mr. McLAUGHLIN'S suggestion on the elevation of the snow-line is very logical. An excellent record could be kept by the use of photography. However, the problem of forecasting on a day-to-day basis will require a daily service of observation similar to rainfall and river gage-stations.

AMERICAN GEOPHYSICAL UNION

TWENTY-FOURTH ANNUAL MEETING

SECTION OF HYDROLOGY

REPORTS AND PAPERS

Washington, D. C.

April 23 and 24, 1943

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REPORTS, PERMANENT RESEARCH-COMMITTEES

SECTION OF HYDROLOGY

WASHINGTON MEETING, APRIL 23 AND 24, 1943

REPORT OF COMMITTEE ON PRECIPITATION, 1942-43

Merrill Bernard, Chairman

Carlos Cabral
A. R. Codd
Leonard B. Corwin
Glen N. Cox
Robert W. Gay
W. G. Hoyt
J. W. Howe
Charles R. Hursh
J. Otis Laws
Luna Leopold
F. T. Mavis
A. K. Showalter
Waldo E. Smith

At the suggestion of President CHURCH, and in accordance with official action of the Executive Committee, the title of the Research Committee on Rainfall has been changed to Research Committee on Precipitation.

The field of the Committee will now embrace all forms of precipitation--rainfall and snowfall, as well as the more unusual types, hail and sleet. Close cooperation with the Research Committee on Snow will prevent oversight or overlap in the transitional phase of the hydrologic cycle from snow as it falls to its position on the ground in the form of the snow-mantle. The snow-mantle in all its aspects will continue to be the principle field of interest of the Committee on Snow.

The Committee has been reorganized and is comprised of the members as above indicated.

It is most encouraging to report that plans have been approved to continue the network of recording precipitation-stations operated by the Weather Bureau in cooperation with the Corps of Engineers, and financed from flood-control funds by the latter agency. The hydroclimatic network of the United States is now made up of approximately 2,600 precipitation-stations, which, together with the 5,400 non-recording stations comprising the long-established climatological network of the Weather Bureau, totals about 8,000 precipitation-stations in all. Over 100 of these, located in the mountainous West, are equipped with shielded-storage snowfall-gages.

The network is being drawn upon to provide synoptic reporting stations of rainfall. These are becoming increasingly important to the operations of flood-control and navigation of the Corps of Engineers and the river- and flood-forecasting service of the Weather Bureau. The reporting networks now in operation are as follows:

No.	Network	Stations	No.	Network	Stations
1	Ohio River	75	5	Yazoo River	10
2	Lower Mississippi River	33	6	Red River	25
3	Upper Mississippi River	26	7	Wallace Lake Reservoir	6
4	Willamette River	18		Total	193

Similar developments are progressing in the Tennessee Valley as set forth in the following report:

ROBERT W. GAY--The network of rainfall-stations in the Tennessee River Basin consists of 381 stations equipped with standard rain-gages, 102 equipped with recording gages, and 21 equipped with radio gages, a total of 504 stations. Upon these and some 84 other gages immediately adjacent to the Basin, the Tennessee Valley Authority relies for rainfall-data required in connection with the activities of the Authority. The number of stations increased during 1942 by eleven standard gages, two recorders, and nine radio gages, a total increase of 22 gages. In adjacent territory, only such gages are used as are helpful in the drawing of isohyetal maps or the computing of averages for areas within the boundaries of the Tennessee Basin. The area of the

Tennessee Valley is 40,910 square miles, so that there is one gage for each 80 square miles on the average. Dividing the area at Chattanooga there is one gage for each 60 square miles in that portion above, or east, of Chattanooga and one gage for each 130 miles in that portion to the west. The greater number east of Chattanooga is due to the more rugged topography in that portion of the watershed.

The recording gages at high altitudes provide valuable information on rainfall in the Southern Appalachian Mountains which has not previously been available.

The radio gages are perhaps the most unusual type of gages in the network. These gages are installed to provide immediate information on rainfall from areas in the valley which are remote from other means of communication. This information is required by the Tennessee Valley Authority water-control and dispatching-engineers who make daily forecasts of stream-flow upon which the day-by-day operation of the various reservoirs is predicated. The radio gages also are important in providing information for river-stage and flow-predictions for construction jobs. Speedy notice of impending runoff is essential to prevent loss of time and equipment, which might otherwise occur whenever there are floods.

The radio gages are in regions from which quick runoff may be expected and which are lacking in facilities for telephone or telegraph. At two-hour intervals, the gages broadcast signals which indicate to the next lowest 0.1 inch the amount of rainfall which is in the gage. The signals are picked up at forecasting centers and are the basis of estimates of flood-flows prior to the time the water gets into the main streams. The signalled amounts represent all the water caught by the gage since the bucket was last emptied, less evaporation. The gages are serviced frequently enough to prevent the bucket from overflowing. The success of the gages is evidenced by the increase in number since July 1937 when the first four were installed. During 1942, nine new ones were added, bringing the total in use up to 21.

ROBERT L. LOWRY--The Hydrographic Section of the International Boundary Commission started about 1932 collecting supplemental rainfall-data in the drainage of the Rio Grande. Since that time the list of stations for which precipitation-data have been collected, and published, has increased to approximately 30 on the American side of the river. In addition to these there are about 50 stations in the Mexican portion of the Rio Grande drainage (or adjacent thereto) for which records are now collected and published.

The records of daily precipitation at each of these stations are now published regularly in the Water Bulletins of the International Boundary Commission, issued jointly by the American and Mexican Sections. So far as known the records published in these bulletins are not published elsewhere. Data in the bulletins show when the stations were established, who is operating them, and the kind of gage in use. On the American side in 1941, there were six recording gages and 22 standard 8-inch gages in operation. The gages on the Mexican side are standard 8-inch instruments in practically every case.

While the records have not been compiled for 1942, the number of stations in operation has been about the same as for 1941. The records of 1942 will be published in Water Bulletin No. 12, which will be out during the year.

WALDO E. SMITH--The greatest change in the hydrologic studies of the Soil Conservation Service in the gathering of precipitation-data has been the abandonment of most of the standard non-recording rain-gage stations on the Coshocton, Ohio, and Waco (Texas) Experimental watersheds in favor of a smaller number of recording rain-gages. Otherwise on these projects and elsewhere on the hydrologic work there has been little change, and observation has continued as hitherto.

The following bulletins in the Department of Agriculture Hydrologic Bulletin series, and all containing much detailed information on precipitation, have been published within the last year: Bulletin No. 2 "Hydrologic data--Blacklands Experimental Watershed, Waco, Texas, 1937-39"; Bulletin No. 3, "Hydrologic data--Central Plains Experimental Watershed, Hastings, Nebraska, 1938-40"; Bulletin No. 4, "Hydrologic data--North Appalachian Experimental Watershed, Coshocton, Ohio."

It will be recalled that Bulletin No. 1 relating to Coshocton for the year 1939 was published in November 1941. Bulletin No. 5 is now in press; this is a detailed description of the agriculture, soils, geology, and topography of the Blacklands Experimental Watershed, which data are essential to the interpretation of the hydrologic data obtained for this area.

It is anticipated that the data on rainfall, runoff, and related information for the 40,000-acre area at Mexican Springs, New Mexico, for the calendar year 1941 and to a certain extent for earlier years, will soon be in press as Hydrologic Bulletin No. 6. This should prove to be especially valuable since 1941 was a wet year in that region and the bulletin will contain much detailed information on storms as observed by closely spaced rain-gages in a region that has hitherto received scant attention in this regard. A paper by L. L. HARROLD entitled "Thunder storms and

runoff at high elevations in northwestern New Mexico," which summarizes some of the high points of this bulletin, is published elsewhere in these Transactions.

In connection with the studies under way at the Coshocton (Ohio) Project, LEONARD SCHIFF has established rainfall-patterns for use in certain hydrologic procedures, and has prepared a paper on this study that is included in these Transactions.

The original records of summer precipitation on the North Appalachian Experimental Watershed have been loaned to the Hydrometeorological Section of the Weather Bureau for an intensive study of the major storm-occurrences during the summer in that region, and arrangements are complete for a similar loan of data from the Mexican-Springs Area.

LEONARD B. CORWIN--W. D. ELLISON, Project Supervisor of the Northwest Appalachian Watershed and Hydrologic studies conducted by the Soil Conservation Service near Coshocton, Ohio, reports that several preliminary analyses in the catch of recording rain-gages as compared with cylindrical rain-gages in the same area is under way.

The Muskingum Climatic Research Center itself has only to report that it is now on a war-time maintenance basis so far as its study of the rainfall and other climatic phenomena in the Muskingum River Watershed are concerned. With the closing of the program of the Work Projects Administration, it was necessary to reduce our activities in this field to obtaining the data from slightly over 200 recording rain-gages located in the 8,000 square miles of the watershed and to checking the records received before filing. It is hoped that it will be possible to tabulate, with the assistance available, some of the records obtained.

WALTER U. GARSTKA reports a project in Michigan under which the performance of six sets of standard and shielded rain-gages are being compared.

Among the unusual storms occurring during the year was that of July 17-18, in Northwestern Pennsylvania and Southwestern New York. This storm and resulting flood were subject to an unusually detailed investigation by the Corps of Engineers, West Penn Power Company, Pennsylvania Department of Forests and Waters, and the Weather Bureau. Subsequent analysis will in all probability give credence to unofficial reports of as much as 30 inches falling in less than ten hours. Seemingly more the rule than the exception, the area of intense rainfall was almost exactly inside a square marked by four official rainfall-stations.

The importance of evaluating and utilizing unofficial observation made by laymen during unusual storms is receiving the serious consideration of those engaged in storm-analysis. During the storm of October 13-17, 1942, in Maryland and Virginia, the Weather Bureau made a radio appeal for unofficial reports of amounts of storm-rainfall with the result that approximately 50 reports were received, many of which were within an acceptable range of accuracy.

In this connection an incident reported by Committeeman J. W. HOWE is of interest: "An interesting precipitation event occurred here last fall. Last spring a farmer living east of town asked if he might borrow a standard rain-gage from the Institute. Professor LANE arranged to lend him one and helped him install it. The farmer then proceeded to read his gage religiously and made a permanent record. On September 9 we had an intense local storm which caused severe flooding in town. Fortunately, rain-gages at the Airport, at the Institute Station, and the five on our Ralston-Creek Area were in operation, but the interesting thing is that the eye of the storm apparently came exactly at the farmer's rain-gage in which six inches of rain were caught in four hours. Other gages caught varying amounts down to 1 1/2 inches. Later the United States Engineer Office sent a field-man in and he subsequently made a nice report on the entire storm. I was amused, however, at the fact that whereas some of our observers in this area have been making readings for almost 20 years it remained for our amateur farmer with his brand new rain-gage to record the biggest rainfall which Iowa City has seen.

CHARLES R. HURSH--Of outstanding significance with reference to rainfall for the calendar year 1942 in the States of Virginia and North and South Carolina is the gradual replenishment of ground-water. Precipitation for the year was generally above normal in the mountain sections. The highest recorded was at Highlands, North Carolina--100.73 inches. Beginning in January, 1942, little ground-water was in storage and the whole Southeastern Region faced a critical hydro-electric power-shortage for the essential war-industries. In local areas this shortage continued well into the year. In general, however, replenishment took place as a fairly continuous increase. Such increase as occurred throughout the summer and fall of 1942 is unusual as this is generally considered a period of soil-moisture and ground-water depletion. The replenishment was actually brought about by a well-distributed high summer rainfall (35 to 45 inches, depending on elevation, at the Coweeta Experimental Forest, in Macon County, Western North Carolina, as compared with 25 to 35 inches for the previous five years' average, 1937-41). This amount of rainfall was sufficient to meet losses to runoff and to actually increase soil-moisture before the beginning of the new water-year. As a result, soil-moisture conditions favored storage of the high December rainfall as ground-water, and at the end of the year stream-flow was very favorable.

Other than local floods in some of the mountain streams of Western North Carolina and in Virginia during May, the nearest approach to general flood-conditions during 1942 for the middle Atlantic States occurred during late December following a rain of low intensity amounting to from 6 to 12 inches in the headwaters of the French Broad and the Little Tennessee rivers. For the high-rainfall belt of the Southern Appalachians, rainfall for the month of December was above normal, ranging from 8 to 18 inches at official stations in Western North Carolina and in North Georgia.

A. K. SHOWALTER--The Hydrometeorological Section of the Weather Bureau in cooperation with the Engineer Department of the Corps of Engineers, is continuing its researches into excessive precipitation.

A series of hydrometeorological reports of standard form is being made available through the reproduction facilities of the Corps of Engineers at Vicksburg. During the past year Hydrometeorological Report No. 2, "Maximum possible precipitation over the Ohio River above Pittsburgh, Pennsylvania," was published in a more generally available edition. This report describes a basic method of computing the maximum possible storm-rainfall. Report No. 1 of this series, "Maximum possible precipitation over the Ompompanoosuc Basin above Union Village, Vermont," is now in press and Report No. 3, "Maximum possible precipitation over the Sacramento Basin of California," is in the hands of the printer. Preliminary work has begun on a similar report for the Pecos River Basin, New Mexico.

In these successive reports earlier techniques have been refined and adapted to meet new problems. Because of the scarcity of rain-gages in the mountainous regions of the Sacramento Basin, a procedure involving percentage of normal seasonal precipitation was employed to secure more detailed isohyetal patterns. The basin was also subdivided into zones of rainfall-homogeneity. The meteorological method employed is described by A. K. SHOWALTER and S. B. SOLOT in a paper entitled "Computation of maximum possible precipitation" [Trans. Amer. Geophys. Union, pp. 258-274, 1942]. Of particular interest is the adaptability of the technique of computation to the quantitative forecasting of precipitation for the basin, and steps are now being taken to make such an adaptation.

It becomes more and more evident, as smaller basins are studied, that the solution to the problem of rainfall-distribution over small areas converges on the dimensions and characteristics of the unit convective cell, which can also be called the local thunder-storm cell. For this reason, at the request of the Corps of Engineers, the Hydrometeorological Section is now engaged in a thorough study of convective storms, including thunder-storms, tornadoes, and hail-storms. A preliminary paper entitled "The meteorological behavior and characteristics of thunderstorms" by GEORGE N. BRANCATO, has already been published. In this study, an attempt is being made to determine the intensity-durations within thunder-storms, using the dense network of stations found in the Muskingum Conservancy District and on several other experimental watersheds of the Soil Conservation Service. The reliability of various-sized networks of rain-gages in sampling thunder-storm rainfall is one of the points in question.

The organization of data on storm-rainfall continues. Many important storms, some dating back to the last century, have been completely analyzed. Prior to any conversion of the rainfall-data to area-depth and duration-depth relationships, mass-curves of rainfall for all recording and non-recording stations are constructed and checked against a thorough meteorological analysis of the storm. This type of study is now being made for all excessive storms as soon as possible after their occurrence.

The tabulation of hourly rainfall-data at all first-order stations by the Work Projects Administration Project has unfortunately been terminated before completion because of war demands on personnel.

The distribution of precipitable water in the United States continues to be studied by analyses of dew-point, radiosonde, and similar data. Some progress is being made in a study of the relation of convergence patterns to quantitative rainfall-forecasting.

At field-stations, microclimatic studies have continued on the relation between city-office and airport rain-gage exposures, in those places where the main activities of the local office have moved to the airport.

The Weekly Weather and Crop Bulletin from time to time brings out climatic data of interest to hydrologists. The Bulletin of March 16, 1943 has a chart of accumulated departure from normal temperatures and precipitation for the entire United States from 1893 to 1942; while another chart gives the same data for an average of four mid-Continent States, Iowa, Missouri, Kansas, and Nebraska. In the Bulletins for the last week of each month appear pertinent data on rainfall-intensities and averages for the coming month.

U. S. Weather Bureau,
Washington, D. C.

REPORT OF COMMITTEE ON CHEMISTRY OF NATURAL WATERS, 1942-43

C. S. Howard, Chairman

Stanley W. Lohman Melvin Romanoff C. S. Scofield T. G. Thompson

The addresses of the members of the Committee during the past year were as follows: Stanley W. Lohman, United States Geological Survey, Lawrence, Kansas; Melvin Romanoff, National Bureau of Standards, Washington, D. C.; C. S. Scofield, Department of Agriculture, Beltsville, Maryland; T. G. Thompson, University of Washington, Seattle, Washington; and C. S. Howard, United States Geological Survey, Albuquerque, New Mexico.

Dr. Dennison asked to be relieved of his duties on this Committee because of a change in his assignment of official duties. He has been replaced by Melvin Romanoff of the National Bureau of Standards.

Most of the members of this Committee have been engaged in war activities during the past year, or longer, and had very little to submit for this annual report. Because of their interest in the chemistry of natural waters these individuals are being retained as members of the Committee

The Fifth Soil-Corrosion Conference sponsored by the Underground Corrosion Section of the National Bureau of Standards was held at the Statler Hotel in St. Louis, Missouri, on March 25-27, 1943. Considerable attention was devoted to the corrosion of iron and steel under anaerobic conditions, particularly as influenced by sulfate-reducing bacteria. The activity of these bacteria is closely conditioned by environmental conditions, particularly as regards reaction, degree of oxidation, etc.

During this year a report giving the summary of the Pecos River Joint Investigation was published. This report, entitled "Regional planning--Part X: The Pecos River Joint Investigation in the Pecos River Basin in New Mexico and Pecos" was prepared by the National Resources Planning Board and has a publishing date of June 1942. The salinity of water from many sources in the Pecos Basin is one of the major problems connected with the use of these supplies for irrigation in the middle and lower basins. This report gives data on the salinity of water from most sources, the sources of salinity, and some suggestions for remedial measures for control of the salinity in the Pecos River Valley.

REPORT OF COMMITTEE ON SNOW, 1942-43

(Presented in abstract by François E. Matthes)

J. E. Church, Chairman W. U. Garstka, Vice-Chairman

Matthew Balls	E. H. Collins	O. H. Hoover	Salvatore Pagliuca
Henry I. Baldwin	E. S. Cullings	Joseph Kittredge	Bestor Robinson
Howard T. Barnes	E. B. Debler	Ray K. Linsley	J. H. Ryan
H. K. Barrows	Carl H. Elges	W. W. McLaughlin	L. K. Sherman
Paul L. Bean	R. C. Farrow	J. D. MacVicar	Alden K. Sibley
Merrill Bernard	D. B. Freeman	James C. Marr	Harlowe M. Stafford
H. P. Boardman	Laurence M. Gould	François E. Matthes	Robert G. Stone
Phil E. Church	G. A. Hathaway	Gerard H. Matthes	Walter T. Wilson
George D. Clyde	Eric Hinton	Lacey V. Murrow	R. A. Work
	William H. Hobbs	Fred H. Paget	

The personnel of the Committee has been continued into the new-triennium. RAY K. LINSLEY, specialist in snow-runoff, J. D. MacVICAR, pioneer in the physics of snow-removal, WALTER T. WILSON, specialist in snow-melting, and WALTER U. GARSTKA, Secretary of the Central Snow-Conference, have been added and the last appointed Vice-Chairman in place of Captain RICHARD C. FARROW now in Europe.

The season of 1942-43

The season has been one of temperature extremes geographically--as usually happens between the East and the West. The East has experienced a severe winter and the West a mild one with rain and floods. Water-storage is heartening in the East and superabundant in most parts of the West.

The narrative is best given in the words of the regional reports:

Newfoundland (ERIC HINTON)--The calculated volume of water in the snow-blanket is 41.1 billion cubic feet or nearly 85 per cent of the previous 17-year average.

New England (PAUL L. BEAN)--The effects of the drouth of 1940-41 are still (March 18) in evidence in Maine, evidenced in relatively low deep ground-water supplies. In northeastern Maine, in New Brunswick, and in the Gaspe Peninsula areas, extremely severe drouth conditions have prevailed. Industrial and domestic water-supplies were seriously affected and an acute shortage of hydroelectric power has existed.

In the rest of the State, the accumulated precipitation is below the long-term average and ground-water conditions have been below normal. The distribution of such precipitation as has occurred has not been of such magnitude, nor occurred at such times, as would permit a satisfactory recharging of normal ground-water. In other parts of Maine, the domestic and industrial water-supplies have been adequate, but water for hydroelectric power has been inadequate to meet war-time demands, resulting in heavy fuel requirements at the steam-generating stations.

The winter of 1942-43 has been exceptionally severe, with temperatures running much below the long-term averages. The temperature has ranged from 38° below zero to 48° F above zero in a period of one week in the month of February, 1943.

The snow-cover started to form in late November on an unfrozen ground and the forest-floor is still unfrozen. This has resulted in a relatively long period to accumulate a snow-cover, with very few thaws.

The snow-cover now shows from one inch to four inches of water-content up to elevation 600 feet above sea-level, four to 16 from elevation 600 feet to 1,000 feet, while above 1,000 feet a water-content of from six to eight inches is indicated.

These figures of water-content of the snow indicate that full storage-reservoirs should be obtained by June 1 with materially less than average precipitation during April and May. Should precipitation from March 15 to June 15 equal minimum records, full reservoirs would not be obtained and deep ground-water supplies will be inadequate.

I regard our prospects as reasonably good for obtaining satisfactory storage-reserves for hydroelectric power. However, when one is operating within a few miles of the boundary-line of extremely dry conditions, that is, practically in the next watershed, caution in estimating future conditions is decidedly in order.

We have continued our coverage of the total area by snow-surveys as in former years, with some few extensions to higher elevations. Conditions of labor and supplies have interfered somewhat with the frequency with which surveys have been made. Fortunately, the prolonged cold weather has not made frequent surveys as essential as in other years.

There is no evidence of severe spring-floods due to excessive water-content of the snow. The ice-cover on the river is heavy and strong, averaging thickness of about 25 inches. This is a distinct flood-danger, due to the effect of ice-jams in the event of an early spring break.

New York: Western Adirondack Region (E. S. CULLINGS)--The accumulation of snow is notable in the uniformity of depth and density over the whole area. The average depth is the maximum recorded on March 1 in the 20 years during which snow-records have been kept. The snow-cover consists of from 24 to 30 inches of dense, coarsely crystalline snow with a surface-layer of from six to eight inches of new light snow. About 12 inches above the ground there is a heavy crust of from one-quarter to one-half inch of ice. There is no frost in the ground.

Hudson River Regulating District (E. H. SARGENT)--The Sacandaga Watershed Snow-Survey of March 1 and 2, 1943, showed the largest snow-water content for that time of the year since records have been kept (13 years).

The measurements varied from a snow-depth of 40.5 inches with a water-content of 11.32 inches at Arietta to 15.2 inches of snow with a water-content of 4.45 inches at Edinburg.

The weighted mean for the watershed was 7.9 inches water-content, equivalent to 19.2 billion cubic feet on the watershed of 1,044 square miles.

A year ago this date the snow-water content was but 4.6 inches against this year's 7.9 inches.

Michigan (W. U. GARSTKA)--For the State of Michigan as a whole, snowfall exceeded all previous records. A paragraph prepared by H. M. WILLS, Director of the Michigan Section of the United States Weather Bureau, on this subject follows:

"Heavy snowfall during the winter of 1942-43 in Michigan--The State of Michigan experienced the heaviest snowfall in its climatological history during the winter of 1942-43. The snow-season opened in October with the largest fall in nine years. November witnessed a total snow averaging nearly eight inches, about two inches above normal. This was followed by the heaviest December

fall since 1929, the State average exceeding 20 inches, or eight inches above normal. January received 25 inches, which is 11 inches higher than the normal amount. The February total stood at 14 inches, or two inches above the past average. In March, the snowfall averaged 16 inches, again exceeding the normal by seven inches, and the winter's fall to date had already surpassed the previous record for an entire season by 7-1/2 inches. The April fall was over six inches, or 3-1/2 inches above normal. The total snowfall for the season averaged 92 inches, or 35 above normal, and 14 inches more than the previous record of 78 inches in 1903-04."

Although the snowfall for the State as a whole averaged 92 inches, the greatest accumulation in terms of water-equivalent at the Soil Conservation Service's experimental watersheds at East Lansing occurred on February 8, 1943, on which date there were 8.2 inches of snow having a water-equivalent of 2.57 inches at cultivated watershed A, 8.4 inches of snow having a water-equivalent of 2.45 inches at cultivated watershed B, and 9.2 inches with a water-equivalent of 2.42 inches at the wooded watershed. The winter was characterized in southern Michigan by a number of thaws which served to keep the snow from accumulating to any great depths.

Colorado (RALPH L. PARSHALL, in Engineering News-Record)--Heavy mountain snows on the principal Colorado watersheds now store sufficient water to insure the State its most favorable irrigation-supply in years. The slogan, "Snow on the mountain tops, assures the harvest of bounteous crops," is the center piece of his February reports.

Alberta-Montana: Bow Basin (O. H. HOOVER)--The survey in the vicinity of Lake Louise, Alberta, Canada, was conducted on March 25 and 26 for 1943.

Snow-depths and water-contents were obtained on eight half-mile courses comprising a total of 125 samples.

The 1943 mean snow-depth for the eight courses was 31.0 inches, which compares with 25.2 inches in 1942 and the mean of 24.8 inches for the previous six years.

The 1943 mean water-content for the eight courses was 6.7 inches which compares with 5.3 inches in 1942 and the average of 5.8 inches in the former six years.

Immediately following the survey a very heavy snow-storm occurred, depositing at least a further foot of new snow in the basin. This would increase the water-content for the survey by at least one inch.

During the month of March the Bow River at Banff was discharging at the rate of 113 per cent of normal.

From the examination as above (not including the snow-storm which occurred just after the survey) it is estimated that the Bow River at Banff for the period April to July may discharge 610,000 acre-feet, which is 100 per cent of the long-term median flow. Including the snow-storm, which happened on the last four days of March and assuming the average water-content on the various courses to have increased to 7.7 inches, it is estimated that the Bow River at Banff will discharge 660,000 acre-feet, or 108 per cent of normal from April to July.

As formerly stated, however, experience indicates that such a forecast may be materially disturbed in this basin by rains in June and July.

St. Mary Basin (C. S. HEIDEL and O. H. HOOVER)--The survey in the Swiftcurrent Creek Basin in Many Glacier National Park, Montana, was conducted on May 5 and 6 for 1943.

Snow-depths and water-contents were obtained on five courses, comprising a total of 72 samples.

The mean snow-depth for 1943 was 61.2 inches, which compares with 31.3 inches in 1942 and 52.0 inches, the median for 22 years.

The mean water-content for 1943 was 28.6 inches, which compares with 13.3 inches in 1942 and 24.7 inches, the median for 22 years.

In comparing the data of 1943 with all previous records it is estimated that Swiftcurrent Creek at Many Glacier for the period May to July may discharge 74,000 acre-feet under normal conditions of precipitation, and this runoff represents 112 per cent of the long-term median flow for this period.

Upper Missouri River Basin (DELBERT B. FREEMAN)--Missouri Headwaters Region: Snow-surveys made by the United States Geological Survey for the Engineer Department during the early part of March 1943 indicated an average snow-cover for the headwaters region of the Missouri River of approximately 50 inches with a water-content of 15.0 inches. This latter figure is about 175 per cent of the average for the previous period of record, that is, 1935-1942, for the early part of March.

As soil-moisture conditions are believed favorable over most of the basin due to fall rains and a thaw in late February, it is anticipated that if the precipitation during spring and summer is average or above, the runoff in the Missouri Headwaters Region will equal or exceed that for

1942, which was the greatest since 1927, and will approximately equal the long time average of about 5,000,000 acre-feet.

Fort Peck Dam: Fort Peck Reservoir, which was approximately one-third full and 140 feet deep on March 1, 1943, is expected to fill to a record high level by mid-July, 1943.

Columbia River Basin (R. A. WORK)--Bountiful water-year is assured. For a few days in January the Seattleites took to skis on a snow-cover of asserted maximum 16 inches.

Columbia River Basin (JAMES C. MARR)--Throughout most of Columbia Basin, the weight and condition of the mountain snow-cover make imminent a large, well-sustained runoff.

The prediction is that there will be no shortage of water for irrigation, industrial, or culinary uses any place in Columbia Basin or West Coast areas this year. The water-problems this year will have to do with protection against high river-stages and regulation of reservoirs to afford maximum flood-protection, and at the same time conserve a maximum amount of water for use after the spring freshets have subsided.

Individually each of the tributary or small mountain watersheds is blanketed with heavy enough snow to produce runoff at least equal to one of the two or three maxima which have occurred during the past 20 years or more.

Assuming that the normal pattern of runoff will occur with regard to the various tributaries of Columbia River, the six-month discharge at The Dalles, Oregon, is estimated at 105,000,000 acre-feet, which ranks with the record runoffs during 1938, 1933, and 1928.

Colorado River Basin (RALPH L. PARSHALL)--The water-content of the snow on the headwaters of the Colorado River averages about ten per cent more than last year at this time and the outlook is quite favorable for a normal runoff.

The Colorado River Water Conservation District (F. C. MERRIELL)--Supplementing the general forecast, this District prepares detailed summaries of data for 14 Western Colorado areas, natural subdivisions of the territory, in each of which local interest justifies a closer approximation of water-supply than the general summary and forecast provide. Accurate numerical predictions for these areas are not practicable, but general indications as to floods and supplies are.

Predictions made at any time, but especially while snow is still accumulating, are subject to change as the season advances. Current weather greatly influences the manner of, and even the final total of, flood-runoff. Autumn weather set up the primary ground-moisture condition, which at high altitudes in Western Colorado was, and still is, dry. At lower altitudes rains and thawing of light snows have increased ground-moisture, although it is still deficient in most places.

The condition described last month (February) persists. There is heavy snow-cover along the Continental Divide, but west of and below this narrow belt, snow-cover and water-content decrease rapidly, with little snow below 7,500 feet. Grand Mesa water-supply is still deficient and White River, the only drainage-area not reaching the Continental Divide, is still deficient at its headwaters. Gains in snow-density, which should increase with the season, have been normal except where water-content is lacking. With normal weather for the rest of the season there will be about the same runoff as in 1942; any apparent excesses in water-content will probably be taken up by dry soil at high altitudes.

Oregon (J. H. RYAN)--Early snows were followed by warm rains and caused near-record floods in January in the area west of the Cascade Mountains. Later snows and more rain left the snow-cover with a high-water content (as high as 45 to 48 per cent on some courses) and this in turn caused minor floods and an early runoff in April. Most of our storage-reservoirs are full and the rest have in storage more than a normal water-supply. Prospects are now very good for adequate water-supplies throughout the State.

Construction of shelter-cabins and lay-out of additional courses are at a standstill and probably will remain at a standstill for the duration.

Despite sudden changes in personnel and the unusually severe conditions of weather, which prevailed during the periods when the snow-surveys were made, measurements were made at practically every station in the snow-survey network this spring.

California (FRED H. PAGET)--The snow-surveys indicate that in the various watersheds of the Sierra there now exists a snowpack ranging in general from ten per cent below normal to ten per cent above. Taken as a whole the snowpack at the present time is slightly above normal.

The outlook is for a good water-year, with ample supply to operate all installed hydroelectric generating facilities, and more than enough for irrigation, industrial, municipal, and domestic uses.

Water will again flow into Tulare Lake from the Kings, Kaweah, and Kern rivers, as the unregulated discharge of these rivers during the snow-melt season promises to exceed the normal demands for irrigation of the agricultural areas which they ordinarily supply.

Nevada (J. E. CHURCH and H. P. BOARDMAN)--In Nevada research weather has continued throughout a second year with abundance of water but unusual accompanying conditions.

The capacity of all reservoirs in the Sierra Nevada and Humboldt Basin has been far exceeded. Lake Tahoe has been under regulation the entire winter in keeping with increase in snow-storage and has again been brought to maximum at 0.08 foot below the stipulated elevation. Thus the inauguration of snow-surveys in 1910 to forecast the seasonal level of Lake Tahoe has been fully justified through decades of low water and high until interstate confidence has been fully established.

To control the Lake during the present year 265,730 acre-feet have been released since November 1 or a depth of 2.15 feet. Pyramid Lake, a historical and scenic feature of western Nevada, has been benefitted as recipient.

In the Humboldt Basin the water-table, now highest of record, has again diverted snow-water into the river-channel in such abundance that the flow during March to July is twice that indicated by the snow-cover. In consequence, the reservoirs even at the foot of the stream were filled early in the season and emptied somewhat to relieve strain on the dams. For the first time in decades, Humboldt Lake has been restored from desert waste.

Divergence between precipitation and snow-cover and between snow-cover at high and low elevations provides opportunity to estimate the quantitative effect of each. For example, at the summit of the Central Sierra as represented by Soda Springs the total precipitation during November to March was 141.8 per cent of normal and the snow-cover on April 1 was only 98.2 per cent. In the Humboldt, the precipitation during November to February was 138 per cent of normal with a residual snow-cover on March 1 at high levels of 91.5 per cent and 42.1 per cent at low. The mild winter that caused rainfall at moderate elevations likewise produced melting. In turn, the unprecedented density of the snow due to frequent melting and freezing caused its final premature melting. The high-level snow, being above normal in quantity and unaffected by mild temperature, is sustaining the late flow of the streams.

Utah (GEORGE D. CLYDE)--The snow-surveys show that there will be water ample for all needs in northern Utah, but potential supplies decrease rapidly toward the south.

Water-conservation is urged so that carry-over storage can be built up to cover future dry years.

Arizona (RALPH L. PARSHALL)--In Salt River the snow-cover is estimated at ten per cent of average as of April 1. But on the Gila, San Carlos Reservoir reached maximum filling of 564,000 acre-feet on March 17 and on the Salt combined reservoir-storage on March 30 was 1,566,000 acre-feet or about 95 per cent of that of a year ago.

U. S. Division of Irrigation (PAUL A. EWING)--The West, with the exception of Arizona, southern Utah, and eastern New Mexico, should have enough water for all crops we can harvest--some sections fear they may even have too much. As far as the West is concerned this is not Herr Hitler's year.

Snow-conferences

These are difficult years for conferences. The Central Snow-Conference at East Lansing was held in the days of Pearl Harbor and the Western Snow-Conference at Pasadena the month following. Thereafter the meetings by the latter planned for Salt Lake City in June and Berkeley in January, 1943, were abandoned.

The meeting long planned by the Section of Hydrology and the Western Snow-Conference at Corvallis in June, 1943, was held despite the final inability of Oregon State College to act as host and the abandonment of its program by the American Association for the Advancement of Science, with whom temporary affiliation had been arranged.

The program which was Western and centered on war service, was as follows [for proceedings see Part III of these Transactions]:

Hydrology's part in the war effort, by Merrill Bernard, Gail Hathaway, and J. C. Stevens

Some accomplishments and developments of snow-surveying since 1935, by W. W. McLaughlin

The Willamette Valley Flood of 1942-43, by Norbert Leupold, Clarence Pederson, and John M. Allison

Snow-study program at Soda Springs, California, by J. E. Church

Stream-flow forecasting by pattern-behaviors, by R. H. Wahle

Prediction of temperature-distribution in frozen soils, by W. P. Berggren

Precipitation-runoff relationship as a basis for water-supply forecasting, by George D. Clyde and R. A. Work

Forecasting runoff for power and irrigation from relatively low-level areas, by E. B. Price and Harry Olsen

A simple procedure for the day-to-day forecasting of runoff from snow-melt, by Ray K. Linsley, Jr.

In keeping with the desire to publish papers irrespective of their oral presentation at meetings, the following papers have been included:

Soil-moisture under a coniferous forest, by H. G. Wilm

Improving stream-flow predictions by use of past records, by C. H. Niederhof

Use of snow-surveys as an aid in flood-control operation of reservoirs, by Fred H. Paget

Three unusual runoff-years in the Humboldt Basin, Nevada: 1940-41, 1941-42, 1942-43, by J. E. Church and H. P. Boardman

A lateral snow-sampler, by R. A. Work, R. W. Childreth, and W. T. Frost

The Snow-Conference approved the change of its name, from Western Interstate Snow-Survey Conference to the shorter, broader name Western Snow-Conference, and thus caught up with its younger sisters. This Conference had, however, always been broad in its programs despite its restrictive name.

About 30 persons were in attendance. The plan was approved of urging membership in the American Geophysical Union while maintaining the Conference as a bond between all workers in snow.

The Eastern and Central Snow-Conferences are restricting their war meetings to committees only.

Research

S. M. KISTNER of the Westinghouse Manufacturing Company has said: "Research is roving the unknown territories ahead independently, yet not without purpose, seeing for the first time what all the following world will see a few years hence."

This purpose and prophecy form a fitting introduction to the snow-research that goes on steadily or even at accelerated pace because of the present need of greater efficiency.

The themes are so diverse and widely distributed that they will be presented mainly as regional reports.

Newfoundland

River-ice (ERIC HINTON)--The following correspondence by Mr. Hinton indicates the increasing value of the Transactions of the American Geophysical Union which are steadily growing toward reference-library size. "Referring to the List of latest publications of USSR, on snow and ice, by B. P. WEINBERG [Trans. Amer. Geophys. Union, pp. 757-779, 1940], we are interested in the problem of frazil- and anchor-ice, also methods of dealing with troubles arising from this source in hydroelectric plants. Weinberg's bibliography mentions several very interesting papers upon the subject written in Russia. We would like to know whether these papers are available either in Russian or translated in English. Papers dealing with the theory of over-cooling of turbulent water in open channels and with forecasting formation of frazil-ice and of ice-cover are also contained in the bibliography. We would appreciate your early attention to our request and any further information that you may think pertinent will be most welcome."

In a letter to J. E. CHURCH Mr. Hinton writes: "I have a copy of Bulletin 23 of the International Association of Scientific Hydrology, Edinburgh Meeting of 1936. The series of papers on the subject of frazil-ice, from Latvia and Russia, indicate that ALTBERG's researches are of most interest to us. For, the discussions given in these papers confirm the observations obtained here. But Professor WEINBERG's list of papers indicates that many more researches have since been conducted in Russia, and it is quite evident that these later data would greatly assist us.

"The paper by J. C. STEVENS [Transactions of 1940, pp. 973-979], to which you refer, is of much interest in that it clearly explains the danger of a large channel becoming completely choked with frazil-ice. In our case, this phase of the occurrence shows that heating the forebay rack-bars, to maintain flow, could produce the embarrassing predicament of choking the canal and the penstocks.

WALTER J. PARSONS' paper on Ice in the northern streams of the United States [Transactions of 1940, pp. 970-973] is most interesting. In following your suggestion I wrote to WALTER

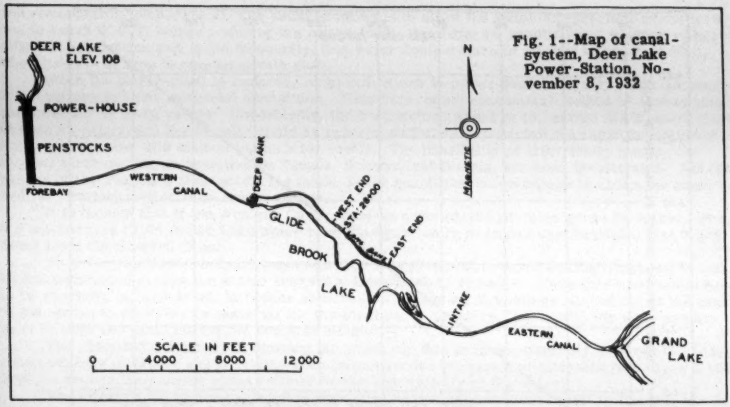


Fig. 1--Map of canal-system, Deer Lake Power-Station, November 8, 1932

J. PARSONS as follows:

"At Dr. Church's suggestion, I am writing you regarding the troublesome problem of dealing with frazil-ice. That you have given this subject considerable study, is evident from your very interesting paper, published in the Transactions of 1940.

"Your paragraph describing the formation of anchor-ice during cold nights and its subsequent release by radiant heat absorbed by the anchoring medium, shortly after sunrise, explains an occurrence that has puzzled us on several occasions.

"Our problem consists of maintaining a flow of 6,000 cfs through the canal-system shown in Figure 1. The mean velocity in the Western Canal is 3.2 feet per sec at full power-plant load and with a minimum forebay water-level of elevation 365.0 feet.

"Local records since 1932 indicate that the winter temperature of Grand Lake water has varied from a minimum of 0.°15 C in 1935 to a maximum of 1.°30 C in 1942. These winter temperatures remain fairly constant when the water is cold enough for the Lake to freeze over. This condition requires a water-temperature of approximately 0.°60 C.

"Winter weather, in the Western Newfoundland, is very erratic, and atmospheric temperatures change rapidly from a maximum of 40° F to a usual winter minimum of -20 to -25° F. Strong westerly winds, accompanied by an atmospheric temperature of 0° F, are common. The relative prevalence of these cold winds, early in the winter, regulates the temperature of Grand Lake water and, if even a partial ice-cover forms on the Lake, the winter temperature becomes fixed until the spring break-up.

"The water of the long canal then becomes very sensitive to changes in temperature. While the deeper, tranquil water in Glide Brook Lake permits the formation of an ice-cover, steady turbulent flow of the eastern and western canals maintains free water-surfaces which provide opportunity for heat-transfer from water to air and finally for frazil-ice formation.

"The consequences of allowing large quantities of frazil-ice to saturate the stream and clog the forebay trash-racks have proved so embarrassing that the present practice is to drop most of the power-load just before frazil-ice forms. In order to do this, the coincidence of natural events, inducing the phenomenon, must be known. Therefore, the necessary instruments have been installed to observe wind-direction, wind-velocity, atmospheric temperature, barometric pressure, and water-temperature. All the meteorological instruments are of the usual standard type. The water-temperature, which is observed, as required at Intake and Forebay is determined by reversible deep-sea thermometers, made by Negretti and Zambra, Limited, of London, England. These are mercury-column instruments graduated in 0.°1 C and 0.°01 can easily be read after a little practice. One degree is represented by one-half inch on the scale. It is thought that these are the best standard instruments obtainable for this purpose. All observations are recorded graphically with respect to time.

"After producing tranquil (or possibly laminar) flow in the canal, by dropping most of the power-load, the formation of an ice-cover on the surface of the canal is awaited. The interval required for this occurrence varies from one hour to several hours, depending upon wind-velocity

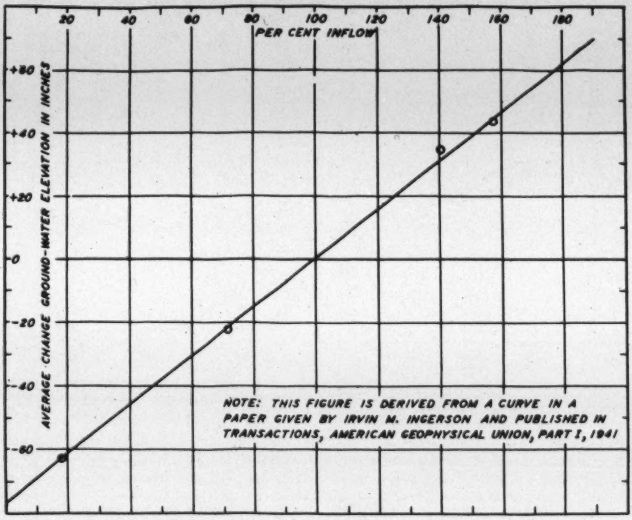


Fig. 2--Relation of inflow to changes in ground-water level, Deer Lake Power-Station, Bowater's Newfoundland Pulp and Paper Mills, Ltd., March, 1943

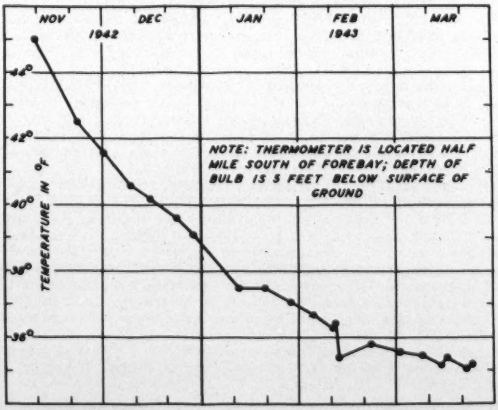


Fig. 3--Soil-temperature, Deer Lake Power-Station, Bowater's Newfoundland Pulp and Paper Mills, Ltd., November, 1942, to March, 1943

and atmospheric temperature. The usual practice is to allow the water-temperature of the forebay to reach 0°.01 C before reducing the power-load. But different conditions of weather require different application and, quite frequently, this water-temperature is allowed to reach 0°.00 C, when its rate of drop is comparatively slow.

"Since the power-plant is isolated, large reductions in power-load inevitably cause serious interruptions to local industrial operations. Therefore, some economical method of overcoming the difficulty is being sought. Undoubtedly, the best method would be to enlarge the Western Canal to such an extent that the velocity could be reduced sufficiently to permit the rapid formation of an ice-cover. But this method is much too costly. The possibility of electrically heating the forebay trash-racks, as practiced in Canada, Norway, and Russia, has been investigated. But the danger of the sustained flow-producing frazil-ice in quantities, large enough to choke the canal and the penstocks, precludes such a scheme.

"It is thought that if the Western Canal could be covered, the problem would be solved. For, the ice-covered Glide Brook Lake would have the opportunity to entrap any frazil-ice that might come from the Eastern Canal.

"To cover the Western Canal water-surface it is proposed to store floating pulpwood in sufficient quantity to occupy the entire area from Deep Bank to Forebay. While this wood would have to be specially cut and dried, to reduce sinkers to a minimum, it would be sluiced out of the canal in the spring to provide raw material for the local paper-industry. Normally, the wood has to pass through the canal during the summer months.

"The proposed deferment of sluicing the wood, for this purpose, naturally involves the additional expense of drying and providing keel-booms across the canal, at intervals (say every 1,000 feet), to reduce the packing effect induced by the high velocity of the water.

"The effect of the increased friction must also be considered with respect to limiting the capacity of the canal, especially at low water-levels when the surface-slope of the water will become much steeper.

"Our calculations indicate that the effect of the floating wood-cover decreases the regulation range of the reservoir water-level by 1.6 feet. But this is a part of the economic aspect of the problem.

"Before definitely recommending the expenditure necessary to provide the floating wood-cover it is desirable to ascertain whether it is really a satisfactory solution to the problem.

"It is thought that the tight mass of floating wood will prevent the rapid transfer of heat from water to air and possibly stop it altogether. Even if frazil-ice did form in small open patches of water, and became entrained in the stream, it is conceivable that the turbulent flow would bring the crystals to the surface, at various points en route, where they would find opportunity to adhere to the wood. During a protracted period of weather favorable to frazil-ice formation, the crystals might accumulate sufficiently to coalesce into a virtual ice-cover.

"I would very much appreciate any comments that you might care to make and trust that our problem may be of academic interest to you."

Soil-temperature and ground-water (ERIC HINTON)--The recommendation, made in previous reports, to obtain soil-temperature records, was carried out. A substantially housed thermograph was installed with the bulb buried five feet deep, in a small sheltered clearing one-half mile south of Forebay. Observations from November, 1942, to March, 1943, are plotted in Figures 2 and 3.

The purpose of this installation is to attempt forecasting the time of the commencement of the spring flood. This is in accord with Russian practice. Whilst local observations for several years may be necessary to establish the relation (if any exists) a study of Russian records inclines me to venture the prediction that the spring flood will commence between April 9 and 14.

Owing to the inaccessibility of the ground-water wells at the western end of Grand Lake, during this snow-survey, it is thought that two more wells, located within reach of the trail used this year, would be useful. Also, depending upon the error of this season's forecast, consideration should be given to the installation of additional wells in other parts of the watershed.

New England: Snow-melting (PAUL L. BEAN)--I am broadening my snow-work this year, but what I am going to find, I do not know. I have constructed a large unit to measure the British thermal units in the snow-cover. The unit has been tested in the laboratory and found sufficiently accurate to be called a calorimeter. This I shall put to work at Aziscohos Dam and run daily tests. I expect to get some light on what meteorological conditions are most effective in melting the snow-cover. I expect later to analyze the effect of varying meteorological conditions on the different layers making up the snow-cover.

Mount Washington and Blue Hill; Physics of snow (S. P. FERGUSSON)--Unexpectedly, on January 28, I have been drawn (I won't say drafted!) into your field again--a rather intensive and extensive program of measuring snow--conducted by Dr. MARK of Brooklyn Polytechnic Institute for the National Defense Research Committee. They borrowed my copy of the report of the Inter-

national Snow-Conference. The equipment and some instructions came a week ago and we began observations at Blue Hill. But we have had no snow worth measuring so far this winter and the work up to now has hardly been more than practice for the observer.

I expect to move the work (or most of it) to our Appalachian Mountain Club Camp at the base of Mt. Washington where JOE DODGE, our very capable manager of the Club's winter activities--skiing and other winter sports--conducts snow-surveys for power-companies in Northern New Hampshire. He evidently used a sampler but I have never seen it and do not know who designed it; but he reports that all instruments on hand need repairs, so, I suppose we have more or less shop-work to do first.

Mr. HAND, Chief of the Weather Bureau's work of solar radiation now stationed at Blue Hill, has made a new sampler of transparent plastic which seems to be promising. The snow-core can be seen through the wall of the tube, consequently, slotting is unnecessary and the only work is that of graduating the scale and securing the cutter in place. The one so far made is only 20 inches long and the cutter is of brass; the chief problem is that of durability and whether the tube will stand use in six feet of snow in the White Mountains.

Metals are hard to get, even with the aid of priorities and how far the bits of steel or dural tubing we have, will go toward repairs remains to be seen.

This snow-project apparently is to last through the next three or four months--means a week of instructing observers at first, then an inspection of their work every three weeks, and, most tedious of all, reports to headquarters. It is possible we may have to analyze the data, for new items spring up every time we discuss the project. If you are cooperating in this work, I shall be glad to exchange data, etc. with you. . . . . .

Our snow-project is slowly coming to a close: At Blue Hill because of less snow than normal and none to measure after March; at Pinkham Notch, chiefly because precipitation has been usually a mixture of rain, sleet, and snow difficult to measure. I spent two weeks there in February and five days in March learning something of different strata of snow, ice, rime, etc., including measuring density, etc., during a breeze of 30 miles per hour when the maximum temperature was -14° F about noon of one day and the minimum -35° next morning--the lowest out-door temperature I ever experienced; this was largely due to radiation during a calm, the wind having stopped before morning. On Mt. Washington, 4,400 feet higher and three miles distant the temperature had risen to -17°. The snow was 50 inches deep in February, increased to 62 by March 1 and had shrunk to 49 on my second visit on March 5. Possibly, we may get a few measurements up in Tuckerman's Ravine (4,000 feet) where snow up to 20 or 30 feet can usually be found in May and June, that is, if there are any occurrences of new snow. It is uncertain whether this project is to continue after this spring; the data on hand may be sufficient.

[Mount Washington Observatory's Icing Research Program for 1942-43 is so essential to present and future transport that it is being reserved for presentation as one of the important projects of the year. J.E.C.]

New York: Snow-melting; Snow and Health (ROBERT E. HORTON)--I have nothing to report (January 19, 1943) excepting the interesting results of a recent storm. We had about four inches of snow on the ground, with a dense surface ice-crust. Then we got 3.5 inches of rain in three days but the temperature remained constant at 33° F. The rain-intensity was low and this rain produced only moderate runoff and did not carry away the snow-cover. It remained at about the same depth as before but water infiltrated through the snow-crust and ripened the snow underneath. This raises a new question and that is the infiltration-capacity of an ice-crust on snow-cover. Also these conditions sustain the idea I have long held: (1) That rain alone is not highly effective in melting snow unless the temperature of the rain is well above the freezing-point; (2) that the presence of a snow-cover does not necessarily induce floods and may have the reverse effect, especially if the snow is deep.

As Chairman of the Soil Conservation Service Advisory Research Committee (not the Committee of the American Geophysical Union) I have recently been asked to advise the Northeast Region of the Soil Conservation Service regarding possible effects of measures by the Soil Conservation Service on human health. This brings in a new and, I think, decidedly interesting question in relation to snow-cover, which I shall not attempt to discuss at length but merely point out the nature of the phenomena.

Many doctors believe, and there is some evidence to support it, that influenza and some forms of pneumonia tend strongly to become incident and epidemic at times when the ground remains bare unusually late in the fall or when bare ground appears for a time after a temporary snow-cover--in other words, that snow-cover is a protection against onsets of these diseases. A typical example was afforded by conditions in eastern New York in late November and December, when severe colds, influenza, and a type of bronchial pneumonia became exceedingly prevalent. One out of three or four persons was laid up, often for a month or two, and I was among the number. Then a cover of snow arrived and the development of new cases stopped quite abruptly.

Obviously a snow-cover prevents the dissemination of dust and bacteria from the ground-surface in the lower atmosphere. On the other hand, it may be that the falling snow completely clears the atmosphere of dust and bacteria and that that is at least a part of the explanation.

Soil-conservation measures, whether they produce good grass-cover or forest-cover, tend to promote both the continuity and duration of snow-cover. If so, snow is a preventive of some of these diseases and it may be that soil-conservation measures can contribute in this way to betterment of health. In any event it appears that here is a question in what may be called medical cryology which is well worthy of research and which has not, so far as I know, hitherto been investigated.

Michigan: Transport, wind-shields, solar radiation (W. U. GARSTKA)--The Highway Section of our Central Snow-Conference of a year and a half ago at East Lansing seems to be bearing fruit. The Michigan Highway Department would have embarked on quite a large program of snow-research as it affects highway maintenance had it not been for a serious reduction in its personnel because of the war. Nevertheless, they have started this in order to get some ideas as to how best to proceed later on

We have had an opportunity to compare with snow-surveys the catch of the three gages at our experimental areas: Ferguson recording gage; a Weather Bureau standard gage; and a Weather Bureau standard gage with a Nipher shield. Our observations indicate that the Nipher shield approximates remarkably closely the snow which we have found to have accumulated by our snow-survey measurements. I will have something interesting to report in this connection at the end of the present winter.

Within the past few weeks we experienced a thaw during which all of the accumulated snow melted with no precipitation. The sunshine was direct and intense. We should be able to get some interesting data on the rate of runoff as affected by solar radiation. Today, on March 6, as I dictate this letter another snow-storm is in action with the snow already having attained a depth of three inches.

Continental Divide: Snow-research (H. G. WILM)--Attached is a condensed statement on snow-research being conducted by the Rocky Mountain Forest and Range Experiment Station in the Colorado Rockies. I sincerely hope you will find this report of sufficient interest for inclusion in your annual report of the Committee on Snow of the American Geophysical Union.

Although our program has been in progress since 1938, we are just now beginning to get some really interesting and worth while results. For this reason and because we have not reported directly to your Committee in previous years, I have taken the liberty of describing our experimental layout in enough detail to show what we are doing.

The Rocky Mountain Forest and Range Experiment Station is doing intensive research on snow-storage and other factors related to water-yield, particularly as they are influenced by the cutting of coniferous forests. Most of this research is centered at the Fraser Experimental Forest, in the headwaters of the Colorado River near Fraser, Colorado, and the Moffat Tunnel Water Diversion Project. Some work is being done also at the Manitou Experimental Forest, in the upper South Platte Basin north of Woodland Park, Colorado.

At Fraser, work is largely concentrated on a group of 20 five-acre plots covered with mature lodgepole-pine. Here data have been collected since 1938 on the storage and melting of snow, interception of rainfall, and soil-moisture deficiencies as influenced by this type of forest. In 1940, 16 of the plots were selectively cut-over, leaving four uncut and four each with commercial reserve stands of 0, 2,000, 4,000, and 6,000 board-feet of timber per acre. Observations taken since cutting have shown a pronounced influence of these treatments on all factors studied.

A smaller, but similar experiment is being conducted to measure the relative effects of aspen, young pine, and open-field cover-types on snow-storage and related factors.

To determine quantitatively the influence of timber-cutting on water-yields, two watersheds have been controlled with stream-gaging stations, snow-courses, and rain-gages. In 1945 or 1946 one area will be cut-over by the cutting method which, based on plot-studies, is then judged to be optimum for water-yield.

Finally, a small experiment has been conducted since 1940 to measure rates of evaporation from snow and to develop, if possible, some easy method for field-measurement of this factor. In connection with this study, tests of the Utah Snow-Sampler have been made to determine whether it is precise enough for experimental work.

At the Manitou Experimental Forest several experiments have been set up to measure the interception of snow and rain by aspen and ponderosa pine, and the relative rates of runoff from snow and rain measured on lysimeters, small plots, and watersheds.

Summary of results, snow-storage and melting-rates:

(1) On the Fraser plots, the amount of water stored in snow in March of each year is inversely affected by the proximity of clumps of trees. On the average, about five inches of water were stored in the center of clumps about 60 feet in diameter, as

compared to 8-1/2 inches in the center of openings of equal diameter. Similar results were observed in stands of young lodgepole-pine, where maximum snow-storage occurred in openings with a radius larger than the average height of surrounding trees.

(2) After treatment of the five-acre plots, snow-storage was found to be greatly increased by this thinning of the forest cover. The two-year average amount of water in snow on uncut plots was 5-1/2 inches, as compared to over eight inches under commercial clear-cutting; the other treatments fell along a straight line between these extremes. Incidentally, rainfall-interception was much reduced and soil-moisture increased by the timber-cutting. Rates of snow-melt were more rapid on the cut-over areas, so that all 20 plots became bare at about the same time.

(3) Snow-storage in aspen stands has been about equal to that on open fields and much greater than under dense young pine.

(4) In three years' records, snow-evaporation from large (500 square feet) pans has been negligible during the winter and has varied from 1-3/4 to 2-3/4 inches of water during the spring melting-period, from about April 1 to May 15 each year. Small weighing-pans, one, two, and four square feet in area, have shown much lower rates of evaporation. All of these pans are located in a large opening in lodgepole-pine, protected from wind but open to insolation and free from interception-effects.

(5) Tests of the Utah Snow-Sampler indicate that it gives results accurate enough for most experimental work, though not sufficiently precise for use in snow-evaporation studies. It was found necessary to have a special spring-balance made by Chatillon and Sons, reading to the nearest 0.10 ounce. Using this balance the standard deviation of repeated water-content readings within a four-foot square was $\pm$ 0.53 inch; this value includes slight variations in water-content of snow on a single snow-board as well as the failure of the snow-tube to cut a true core and the error of the balance. As compared to cores cut with an eight-inch cylinder, the Utah tube gave water-contents on the average about 2.4 per cent low.

(6) At the Manitou Experimental Forest, interception of either snow or rain amounted to about 20 per cent of the average storm--0.04 to 0.05 inch of water per storm.

Because of keen interest in the subject of runoff the following excerpts, referred to in Mr. Wilm's comments, from the annual report of the Rocky Mountain Forest and Range Experiment Station by CHARLES A. CONNAUGHTON are given below.

Based on two seasons' observations, an average of only 5.5 inches of water has been stored in snow on uncut plots as compared to 8.1 inches on commercially clear-cut plots supporting mature lodgepole-pine, a difference of 2.6 inches in favor of the cut-over area.

In spite of greater amounts of snow on cut-over plots, they became bare at about the same time as the uncut plots, owing to more rapid rates of melting under the reduced shade of a more open timber-cover.

Losses of water due to transpiration and evaporation during the summer amounted to about 1-3/4 inches of water from the top 18 inches of soil on uncut plots covered with mature lodgepole-pine. On commercially clear-cut areas the corresponding loss was only about 0.13 inch of water.

The amount of water present in 18 inches of soil on these plots in the spring, just after disappearance of snow, averages about 16.7 per cent of weight, or about 4-1/2 inches of water. This amount of water is equal to about twice the moisture-equivalent of the soil.

Evaporation of snow on a 500-square-foot pan amounted to about 1.75 inches of water between April 1 and May 15, 1942, as compared to about 2.15 and 2.75 inches in 1940 and 1941. Weighing-pans, one and two square feet in area, gave lower results--about 1.00 inch in 1942.

Aspen appears to be at least as beneficial and may be better than young lodgepole-pine in establishing favorable watershed-conditions.

The water-yield from a controlled watershed in the Main Range was about 789 acre-feet per square mile of drainage-area for the water-year 1942, as compared to approximately 632 acre-feet in 1941 and 367 in 1940. Precipitation producing stream-flow was approximately 21.5, 24.3, and 21.9 inches in 1942, 1941, and 1940, respectively, thus indicating the effect of factors other than amount of rainfall on water-yield.

Of the total yield of water from this watershed in 1942, 593 acre-feet per square mile resulted from winter snow and precipitation (mostly snow) during the spring thaw. This was 62 per cent of the snow available for runoff-production (17.92 inches of water), as compared to 51 per cent resulting from 15.98 inches of snow in 1941 and 32 per cent from 13.18 inches in 1940.

Stream-flow resulting from either snow or rain may be predicted with fair precision from data on precipitation and a figure expressing the hydraulic gradient of ground-water.

On untreated plots under young ponderosa-pine in the Front Range, ten per cent of the annual precipitation appeared as surface-runoff, as compared to 17 per cent on plots from which the surface-litter and duff were removed in 1941.

In the year ending October 31, 1942, about 57 per cent of the total precipitation was lost by evaporation from coarse granitic soil in small lysimeters.

In order to estimate average infiltration-rates on 300-acre pastures within a range of ten per cent from the true value, at least 36 small infiltration-plots are required per pasture. The observations may, if necessary, be taken over two or more seasons.

During the year ending September 30, 1942, no appreciable difference in surface-runoff was observed on plots in the bunch-grass type protected from grazing for five years, as compared to plots moderately grazed by cattle in 1942.

Forest influences experiments in the Main Range are designed to determine the relative influence of different types and densities of forest-cover on water-supply. In one set of 20 methods of cutting plots, studies are under way to determine the influence of a virgin lodgepole-pine forest and of four intensities of selective cutting on snow-storage and melt, rainfall-interception, and stemflow, and soil-moisture deficiencies. In treatments applied in 1940, four plots were left uncut, and four each with commercial reserve stands (trees over 9.5-inch diameter at breast height) of 0, 2,000, 4,000, and 6,000 board-feet per acre. In addition undesirable trees were removed from one-half of each treated plot as a stand-improvement measure.

In another study aspen and young lodgepole-pine are being compared with open grassy areas, to determine the relative effect of these cover-types on snow-storage and rainfall-interception. Another small-scale experiment measures rates of evaporation from snow. And, finally, to obtain data on actual water-yields from virgin and cut-over areas, two watersheds supporting lodgepole-pine and spruce have been controlled by means of snow-courses, rain-gages, and stream-gaging stations. After five to ten years' calibration one of these areas will be cut-over and subsequent water-yields compared with yields observed before treatment.

During 1942 more work and emphasis were devoted to the Main Range than to the Front Range, since these experiments promise results of more immediate utility. And although even here research was curtailed to a practical minimum, a number of profitable findings are available.

Snow-storage and melt on plots in mature lodgepole-pine--Two years' records taken since the application of timber-cutting treatments to the lodgepole-pine method of cutting plots show that the treatments have exerted a real effect on the amount of water stored in snow before melting begins each spring. Timber-stand improvement following commercial cutting exerted no appreciable influence. The results are shown in Table 1.

Table 1--Average water stored in snow under mature lodgepole-pine, March 1941 and 1942

Stand improvement	Reserve stand under major treatments, board-feet/acre				
	11,890 (uncut)	6,000	4,000	2,000	0
	inch	inch	inch	inch	inch
Improved	5.35	7.25	7.80	7.62	8.42
Unimproved	5.75	6.55	7.05	7.72	7.88
Average	5.55	6.90	7.42	7.67	8.15

As the melting season progressed the differences between plots in water stored in the snow were reduced because of the slower rate of melt under the denser timber; and the plots all became bare at about the same time.

Soil-moisture deficiencies on the timbered plots--In order to determine the effect of timber-cutting on soil-moisture, the soil was sampled to a depth of 18 inches at ten locations in each of the 20 plots in September, 1941, and in May and June, 1942. The observations during fall provided data on soil-moisture at the end of the summer growing-season and the spring observations, taken just after the snow had left the plots, data on approximate field-moisture-holding capacity. The difference between these observations was an estimate of moisture-deficiency, in the column of soil above parent material, which occurred during the summer season.

Moisture-deficiencies in this first year of a three- to four-year study were found to be significantly related to the intensity of timber-cutting, as were autumn soil-moisture contents, after adjustment to the average content of fine material in the soil. These results are shown in Table 2.

Table 2--Influence of timber-cutting on soil-moisture and moisture-deficiencies

Factor	Reserve stand under major treatments, board-feet/acre				
	11,890 (uncut)	6,000	4,000	2,000	0
	Grams per 100 grams of oven-dry soil				
(a) Autumn soil-moisture (adjusted)	9.89	11.37	12.20	11.55	15.58
(b) Deficiency	6.52	5.64	5.15	4.45	1.18
(c) Field-capacity = [(a) + (b)]	16.41	17.01	17.35	16.00	16.72

The observed values may be converted roughly to inches of depth of water by expressing them in terms of volume per unit-volume of soil. Assuming an average volume weight of 1.50 for this soil, the volumetric deficiency on the uncut plots is 9.78 per cent (6.52 × 1.5); that on the plots with no commercial reserve stand is 1.77 per cent. In inches of depth for an 18-inch soil-column, the corresponding deficiencies are 1.76 and 0.32 inches of water--a deficiency which must be replaced by precipitation before replenishment of much water can occur.

Comparison of interception in stands of young lodgepole-pine with aspen and open fields--The largest amount of snow was stored under aspen, with open fields second and pine a poor third. In March 1942, aspen contained 8.80 inches of water in snow, the open fields 7.61 inches, and dense young pine 6.72 inches. The differences among these values are much greater than might be expected by chance. Pine, however, showed the slowest rates of melt; a little snow remained in this type on May 22, while it was all gone under aspen during the preceding week, and on the open fields before May 15.

Interception of summer rainfall was almost identical under both aspen and young pine--about 0.83 inch, or 20 per cent of 4.17 inches of rain occurring in 17 storms. Stemflow was negligible in both types--only one to two per cent of the precipitation.

As a preliminary conclusion, aspen seems to provide watershed-conditions at least as good as those under a cover of young lodgepole-pine. Aside from the above results, aspen seems to develop a soil-profile which is more permeable than soils under pine, and is quite stable from the viewpoint of erosion.

During the study of rainfall-interception of aspen and young pine, net rainfall was sampled by moving rain-gages after each storm, as was done in an early study in mature lodgepole-pine. By this method 50 locations in a single season were sampled--some with two storms--by the use of only five pairs of gages in each type. The resulting average figures on net rainfall were accurate within limits of about 8.7 per cent (standard error = $\pm$0.008 inch of rain per storm).

Evaporation of snow--From April 1 to May 15, 1942, about 1.75 inches of water were lost by evaporation from snow stored on a circular pan 500 square feet in area, located in a large opening in a stand of lodgepole-pine. Corresponding data for 1940 and 1941 were 2.15 and 2.75 inches. Because of a number of known but unmeasurable errors these results can be considered only indicative and not quantitative. The largest of these errors are probably: The difficulty of estimating the actual water-content of snow on the pan at any time, without excessively disturbing the snow; the inherent inaccuracy of rain-gages and snow-boards in measuring snowfall and mixed rain and snow; and the unknown lateral movement of melt-water on crusts inside the snow-column.

The observed data for this large pan are considerably higher than results obtained with small weighing-pans. For the spring in 1941 a total evaporation of 0.55 inch of water was recorded in pans of area 1.0 square foot and 0.36 inch in pan of area 4.0 square feet. As the smaller pans seemed too small and the large ones too unwieldy, in 1942 pans of area 2.0 square feet were compared with the one-foot pans. From April 3 to May 15, 1942, 1.01 inches of evaporation were recorded in the smaller pans, and 1.03 inches in the larger ones.

Watershed-studies--Hydrologic data for three years are now available for the Fool Creek Watershed in its present untreated condition. At least two more years of records will probably be required to establish reliable average data on water-yields before a treatment may be applied. In the meantime, preliminary hydrograph-analyses indicate that the precision of experimental results may be greatly augmented by statistical control of the observed water-yields.

For example, on each year's hydrograph the runoff from snow-melt was separated graphically from base-flow and runoff due to rain. By interpolation of two depletion-curves the snow-hydrograph was split into three portions, each associated with a measured amount of snow-melt.

With the resulting nine values (for three years), a regression was calculated of stream-flow on snow-melt and on a factor estimating the average hydraulic gradient of ground-water for each runoff-period. By means of this regression about 70 per cent of the variation in stream-flow between periods was accounted for and a similar regression for runoff from rain accounted for 71 per cent of the variation.

In the course of these analyses it was found that in 1940 about one inch of water was lost from the snow-column before any appreciable increment in stream-runoff was observed. Corresponding figures for 1941 and 1942 were 2-1/2 and 3 inches. It is rather informative to compare these rough estimates of moisture-deficiency on a 709-acre watershed with the corresponding figure--about 1-3/4 inches of water--for 18 inches of soil on the uncut lodgepole-pine plots in 1941. Since all of these data are only estimates, the indicated agreement may be coincidence; but it rather appears as though most of the autumn soil-moisture deficiency on this area and cover-type may be found near the watershed-surface, within the root-zone of lodgepole-pine.

As to actual runoff from Fool Creek in 1942, a total of 875 acre-feet (14.81 inches depth on 709 acres) passed through the stream-gaging station. Of this amount, 652 acre-feet (11.04 inches) resulted from 15.62 inches of water made available by the melting of stored snow and by precipitation (mostly snow) during the spring melting-period, 35 acre-feet (0.59 inch) was produced by rain, and the remainder (188 acre-feet, or 3.18 inches) consisted of stable, perennial base-flow. These data confirm earlier findings that, aside from base-flow of mixed origin, most of the water-yield from Fool Creek, a typical high-altitude Rocky Mountain stream, is derived from melting-snow.

Use of this type of analysis employed in dealing with data for Fool Creek should make it possible to compare water-yields before and after treatment with greater precision and shorter periods of study than might otherwise be required. The suggested procedure, applied to two experimental watersheds, one to be treated (A) and one untreated (B), is as follows: Compute a regression of stream-flow from (A)--from either snow or rain, handling each separately--on precipitation and ground-water gradient and also on stream-flow from (B), before and after treatment of (A). Then test the coefficients of the two (before and after) regressions for the significance of the difference between them; test also the difference between the mean water-yields from (A) before and after treatment, adjusted to the mean values (over both periods) for precipitation, ground-water gradient, and stream-flow in (B). This comparison should largely remove the effects of any climatic variation on yields from (A), leaving only the effect of the cutting-treatment and of any remaining uncontrolled factors.

Early in 1942 a second watershed--East St. Louis Creek, adjacent to Fool Creek--was controlled by means of a snow-course, one recording rain-gage, and a cheap and easily constructed stream-gaging station. The whole purpose of controlling this area was to provide comparative data on water-yields from Fool Creek before and after treatment.

A graphic and decisive picture of the influence of a pine-forest on water-supply in the Main Range is beginning to appear from these studies. It appears as though uncut mature pine may be desirable for flood-control or stream-regulation because it prolongs snow-melting and may result in large losses of water. For the same reasons it may be undesirable strictly from the standpoint of water-yield. As compared to heavily cut-over lodgepole-pine, an uncut forest might induce the loss of as much as three to six inches of water per year--perhaps 200 or more acre-feet per square mile of watershed-area.

Also, it begins to appear that aspen stands need not be converted to pine in order to promote optimum watershed-conditions; judging from early results, aspen itself may be at least as beneficial as pine.

Even though these results are only tentative, the conclusions are of immediate usefulness. Without them, heavy cutting of lodgepole-pine for needed forest-products might be feared as improper exploitation of watershed-resources; with them it is realized that cutting properly done may benefit the supply of water, which is even more important in the Rocky Mountain Region than timber for its use in producing essential agricultural products.

Plans for 1943--No new experimental projects are planned for 1943. Tentatively it is planned simply to maintain going projects of post-war and long-time importance, deriving as many results of current usefulness as possible. In addition, wherever feasible, help will be given the other divisions in work of immediate war-time utility. Since the division of forest influences has already lost one technical man by transfer to range-management and is likely to lose another before the field-season; and since field-assistants are difficult to employ, the plans outlined above represent the probable limit of accomplishment.

Western Colorado: Snow-density (F. C. MERRIELL)--For several years, work with the records of snow-course readings has indicated that both time and snow-depth at any given date were factors in increasing snow-density. The curves platted on Figure 4, with snow-depth and

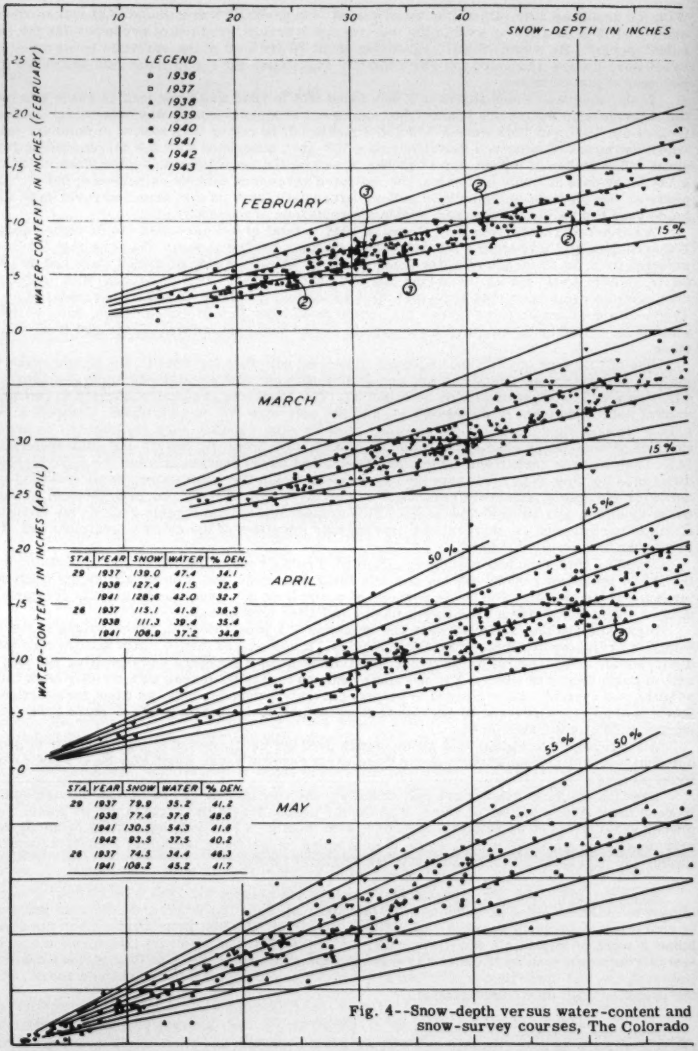
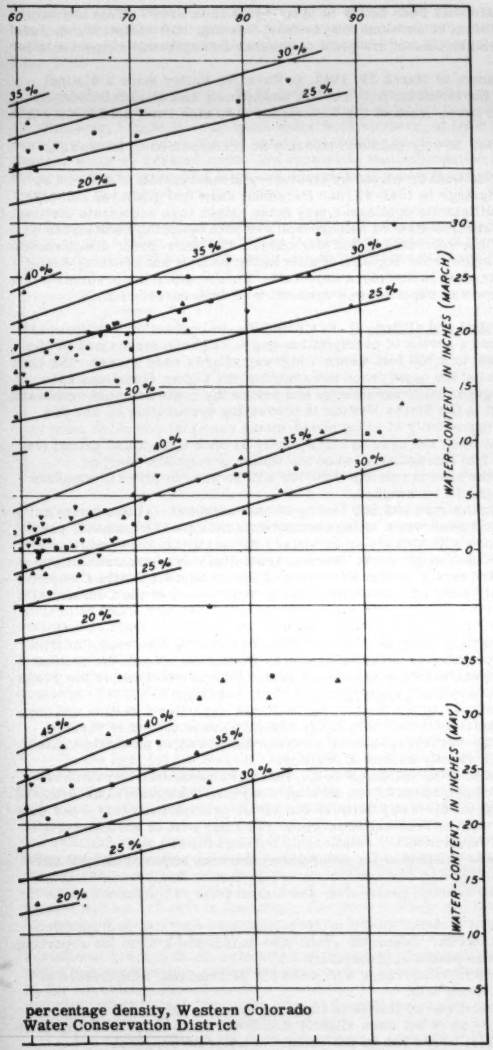


Fig. 4--Snow-depth versus water-content and snow-survey courses, The Colorado



percentage density, Western Colorado Water Conservation District

water-depth as arguments confirm this idea. All the points of record for Western Colorado are platted, with the years distinguished by different signs. Trial platting indicated that there is no relation between altitude and any of the platted values, due to the size of the region and the diversity of exposure and other conditions.

The seasonal tendencies seem to be well illustrated in Figure 4. Compared with the values of February 1, those for March 1 have advanced to the right and upward, while on April 1 and May 1 the upward movement is more strongly shown, but the effect of melting has tended to move many points to the left, especially on May 1.

The facts shown in these plats were first sensed several years ago and led to consideration of density in forecasting along with the more usual weight given water-depth. Studies of altitude-belts and of local and general exposure have not seemed to promise very much in the way of consistent results but may later be reduced to record if there seems to be any sound conclusions to be drawn from these studies.

Great Basin: Sagebrush, snow-melting, and artificial reseeding (JOSEPH H. ROBERTSON)--Cleared land held snow ten days to two weeks later in March 1942 than adjacent land covered by sagebrush. This observation was made by the Intermountain Forest and Range Experiment Station in northwestern Nevada in connection with artificial revegetation-research.

Interception-loss and hastening of melting by long-wave radiation from sagebrush were apparently responsible. This was correlated with two weeks earlier growth of grasses in the brush, lower soil-moisture content throughout the growing season, and earlier depletion of available soil-moisture in the surface-foot than in narrow, cleared strips through the brush. The evaporation- and transpiration-factors were not segregated.

Success of artificial revegetation has been better in clearings than in brush. This has been attributed to competition. The relation of snow-melting to frost-heaving, soil-temperature, and soil-moisture in connection with establishment and yield of grasses on sagebrush range-lands is suggested for further study.

The terrific wind- and dust-storm of March 29, 1943, in Paradise Valley made a distinct change in the color of the snow to the mountain tops and has undoubtedly had an accelerating influence on snow-melting since that time. Most of the dust appeared to rise from the 11,000-acre burn of 1942.

Sowing seed on snow is useless. Sowing should preferably be accompanied by harrowing.

(The problem of dust-effect could best be solved by laboratory measurement. As shown by photographic comparison at Soda Springs in 1941-42 [see Perennial snow and glaciers, Sci. Mon., March 1943], opaque material if sufficiently continuous may delay rather than accelerate melting. During the past winter an unusual accumulation of smoke-dust was noticed on the snow-cover as a result of the heavy railway-traffic accelerated by the war effort. The snow-cover disappeared one month early but the snow was superdense because of alternating melting and freezing during the winter. The effect of the smoke-dust is therefore uncertain. Furthermore the premature melting occurred wherever the snow was superdense irrespective of dust-cover. J.E.C.)

Ruby Mountains, Nevada: Rainfall and altitude (J. E. CHURCH)--In connection with forecasting the runoff of the Humboldt River, a series of precipitation-gages has been maintained up the slope of Lamoille Canyon from 6,200 to 8,800 feet where a highway affords easy access. But lack of caretakers and difficulty of knowing the occurrence of rainfall at the higher elevations have prevented the measurement of the gages after each storm and before the contents could evaporate.

The success at Donner Summit in the Sierra Nevada in preventing evaporation by use of a covering of oil and the consequent opportunity of using broad-mouth cans that can catch snow as well as rain now make it possible to visit the cans as infrequently as once a week and extend the season of observation from March 1 to November 1, when the winter precipitation begins.

In the early and late weeks of the season calcium chloride will be used to prevent complete freezing of the contents and the cans will be weighed.

Seven points of measurement in the rise of 2,500 feet have been selected. At two points daily observations can be made by resident observers. Fragmentary data indicate that summer precipitation does not necessarily increase with altitude as in winter, that is, within the elevation of maximum. Four cooperators will share in the work: Nevada Agricultural Experiment Station; United States Weather Bureau; United States Forest Service; and Elko-Lamoille Power Company. The project may throw further light on the effectiveness of the summer rains of the Continental Divide on its runoff.

Sierra Nevada-Cascades: Physics of snow (J. E. CHURCH)--Paralleling the project at Blue Hill and Mount Washington are the projects at Soda Springs, near Donner Summit in the central Sierra Nevada, and in Crater Lake National Park in the Cascades. Both are outlined in the Transactions of the Regional Meeting at Corvallis [Transactions of 1943, Part III].

The former, conducted cooperatively by the Nevada Agricultural Experiment Station and the United States Weather Bureau, embraces (a) the study of the comparative accuracy of various types of precipitation-gages and snow-surveying under the severe conditions of mountain weather and (b) the effect of temperature and density on rate of melting.

Ten precipitation-gages are under observation; of these, three are recorders and two have a capacity of 20 to 40 inches of water and a range of two months to a year. The general accuracy of all gages was noteworthy. But the great diversity between the winter precipitation (141.8 per cent of normal for November to March) and the residual snow-cover (98.2 per cent of normal April 1) proves conclusively the mutual and supplementary relationship between the two methods.

Complete equipment has now been assembled for determining the heat required to melt snow and trace the movement of water through it. For the former a calorimeter has been assembled that should yield accurate data on the density, grain-size, and temperature of the snow and the heat required to melt it.

ROY E. LUNDQUIST has prepared a classification of snow- and ice-types that has been provided with a metric cross-section sheet for measuring grain-size in mm and a form for reporting the daily observations by check-marks placed appropriately.

PHILIP LIGHT has suggested a telethermoscope with units for determining temperature at various depths in the snow and underlying soil.

The movement of water in the snow can be traced in time and space by the use of the dye Fuchsine that remains dormant in dry snow but when slightly moistened turns red and accompanies the water. By use of the snow-sampler cores can be cut quickly to trace its progress.

The project at Crater Lake, Oregon, cooperatively conducted by the Division of Irrigation of the United States Soil Conservation Service and the United States National Park Service, has been

suspended by the winter closing of the Park. It is a study of the evolution of deep snow-cover and has resulted in the development of a lateral snow-sampler for cutting cores at any angle or depth in the snow. Its operation is illustrated in the article on Meteorology in the Britannica Book of the Year 1943.

Arizona: Sublimation (G. E. P. SMITH)--The gage-station at Glenwood Springs, New Mexico, is very well placed for correlation with the work which we have done or shall do at Alpine.

However, I doubt if we do much more work up there, at least for the duration. We desire, of course, to be there when the Sun shines and the dry winds are blowing, but twice the weather has changed while we were en route. We appreciate that sublimation is unimportant in wet weather, but are trying to prove that there are occasions in some years when the losses of snow may be very great in a period of a few days.

Snow and ice-crystals (GORDON L. WALLS)--Whenever during the cold months I hear snow patter on the window, I always hasten to catch and examine some, in the hope of finding that the flakes are conical (I have been lucky enough to witness two such falls, both some years ago, in Ann Arbor).

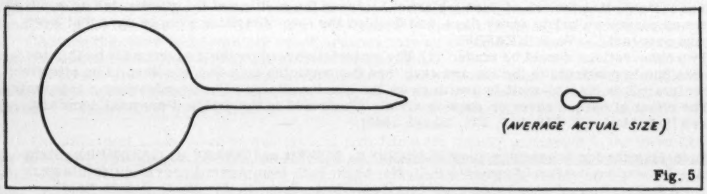


Fig. 5

On some day late in March of this year I was working in one of our range-finder testing towers (Bausch and Lomb Optical Company) when some "noisy" snow fell for a period of some minutes. I was practically outdoors, wearing black gloves which were good and cold, so I caught some flakes in my hands, half-expecting them to be conical or "tapioca." But they were quite a surprise as they appeared to be of clear ice (though I do know enough not to speak of "hail" in March), and while many were irregular a surprising percentage were spherical, with a slender protrusion which was scarcely expanded at its base but ran straight for a way and then tapered as indicated in Figure 5. These forms reminded me of nothing so much as the glass-headed tacks with which one keeps track of movements of troops on a military wall-map. The points were fragile so that I have no doubt that most would be broken upon hitting anything harder than leather, which may account for the fact that they went unnoticed--at least, there was nothing about the phenomenon in next day's paper.

(The note on Hail shells by CHARLES F. BROOKS [Bull. Amer. Met. Soc., p. 53, 1943] may cast light on their origin; this note is quoted in full below to stimulate further observation. J.E.C.)

"In the Bulletin for March, 1941 [v. 22, p. 116], D. L. ARENBERG described hail with liquid water inside that he observed on Blue Hill, August 23, 1940. I can now report another case, at Silver Lake, New Hampshire, June 28, 1942. A sharp shower moving slowly from the mountains a few miles northwest developed into a thunder-storm with hail from $11^h\ 15^m$ to $11^h\ 25^m$ in the morning, locally whitening the ground. The precipitation was 0.46 inch. The hail was rather flat, and ranged in size mostly from 5/16 to 7/8 inch in greatest diameter, from 1/4 to 2/4 inch crosswise, and from 3/16 to 3/8 inch in thickness. The largest stones were with some sharp points on the periphery, more or less irregular in outline, and had protuberances like nearly clear rims on one side. One had five from 1/16 to 1/8 inch in diameter sticking out about 1/8 inch from the central portion 1/2 inch in diameter. The general shape and the bubbly interior, though with clear-ice margins, gave every impression that the hail was simply of hastily frozen, large wet snowflakes.

"In fact, some of the hail consisted of only a hollow shell 1/16 to 1/8 inch thick, but 3/4 inch across and 1/4 inch thick, evidently a hailstone which was still partly liquid when it struck, but which had cracked open and let the water out. I found one stone that had the unfrozen water still in it, for the bubbles moved about as it was tilted. As the hail melted some of the stones became complete rings of ice. The outer edge of the hail had frozen more than the inner portions, presumably because of the greater flow of air.

"The smaller stones had a nearly spherical core of hard cloudy ice 1/4 inch in diameter, with a tapering equatorial shelf of clear ice 1/8 inch wide.

"The air-temperature before the storm was about 70°F and the air calm. There was a moderate northwest squall when the hail began and a southeast squall when it ended as the storm moved on to the southeast. The air-temperature fell to about 60°F. The hail was all melted in an hour."

Accelerating glacier-melting (W. U. GARSTKA)--The following clipping [Christian Sci. Monitor, February 15, 1943] refers to a reputedly Russian method of accelerating the melting of glaciers and ice-masses by covering them with a layer of black soil. I was very much interested in learning of this Russian development as we know the radiation in the Arctic regions is quite intense, due to the clarity of the atmosphere. One can leave it to the Russians to take practical advantage of this fact.

"How blanketing a glacier might provide more water for irrigation: Soviet engineers are experimenting with a plan to increase the supply of water for irrigation in Central Asia. The water for the crop-land in that region comes from the melting of ice in a glacier in the near-by mountains. In an effort to increase the volume of water available for irrigation (and thus to increase the yield of the cultivated land) the Russians are experimenting with a plan to cover part of the glacier with a thin layer of dark, dull-surfaced, heat-conducting material. Results so far obtained indicate that the use of such a blanket hastened the melting of the glacier-ice as much as four times normal on bright sunny days, and doubled the rate of melting even on days that were gray and overcast."--W. P. KEASBEY.

Two observations should be made: (1) The material spread on the glacier must be thin to allow the Sun to penetrate to the ice and even then the particles may sink too deep to be effective; (2) acceleration in glacier-melt is overdrawing the glacier-storage like overdrawing a reservoir.

The effect of opaque cover on snow is vividly illustrated in the article Perennial snow and glaciers [Sci. Mon., pp. 218, 219, 221, March 1943].

Strip-planting for conserving snow (HAROLD E. TOWER and HARRY H. GARDNER)--Strip-cropping for war production [Farmer's Bull. No. 1919, U. S. Dep. Agric.] provides two illustrations: "A buffer strip of corn holds snow (maximum knee-deep) in this North Dakota field" (Fig. 31); and "Contour listing beanfields in the fall prevents soil drifting, catches and holds snow, and prevents runoff" (Fig. 36).

Snow-ridging is becoming an established usage in the windswept prairie States and provinces, but its maximum value depends upon the depth of the snow and the water-need of the crop. For details see "Observations on snow cover as affecting farm crops" by P. O. RIPLEY, "Snow utilization in prairie agriculture" by G. D. MATTHEWS, and "Snow ridging to conserve moisture" by THOMAS E. LONG [see Proc. Cen. Snow Conf., pp. 116-137, December 1941].

Snow- and ice-life

For the nature enquirer, the following notes on microbes, algae, and fish are included.

"According to Professor WALTER L. MALLMANN of the bacteriology department, snowflakes are generally sterile, especially if it has been snowing for some time. Snow or rain will collect dirt, bacteria, and spores from the air, however; and in the improbable event of a violent dust-storm, followed by a rain or snowfall, the individual drops or flakes would be impure. But a petri dish exposed to the open air in a snowstorm would collect virtually no bacteria."--BARBARA HAFFORD in Michigan State News, Michigan State College, East Lansing, Michigan. (Dr. Mallmann plans to continue his study of the bacterial content of snow during the coming winter.)

"Algae are the simplest forms of plant-life. They also are extremely adaptable, being found to flourish under widely varying conditions. Some types of algae, for instance, may be found in hot springs, growing at temperatures as high as 167°F. Other algae, on the other hand, are equipped to thrive in ice or snow, shunning temperatures above 39°F. These latter varieties may be found covering large areas of the eternal snow-fields of the Alps, the Pyrenees, the Carpathians, the Urals, the Andes, and the Sierra Nevadas, where they give the snow a rosy tint. They sometimes occur in such abundance as to splash the snow with crimson, and are the cause of so-called "red snow."--Christian Science Monitor.

"Wherever life can get a toe-hold on Earth it has established itself. Some of its strangest manifestations are minute plants--single-celled organisms which belong to one of the most primitive groups of living things--that appear to live in infinite numbers on perpetual snow and ice.

"Glaciers and snow-fields 'bloom' with vivid reds and violets. Perhaps this is the most inhospitable of all the realms of life has invaded. The phenomenon naturally is quite rare. Only a peculiar environmental complex makes it possible. A report of an intensive study of the manifestation in Alaska, made in 1936 by ERZSEBET KOL, Hungarian woman scientist, has just been published by the Smithsonian Institution. Miss Kol worked under a Smithsonian fellowship.

"She collected the snow and ice algae from snow-fields and glaciers in widely separated Alaskan mountain ranges and found nearly 50 examples of the phenomenon. Specimens were obtained from each for taxonomic study and Miss Kol had planned to cultivate them at a laboratory established at an altitude of 11,382 feet in the Jungfrau Pass in Switzerland. What effect the war has had on these plans is unknown since it has been impossible to communicate with her since the United States entered the conflict. Material which she had preserved alive was lost in 1940.

"Life of any kind in such an inhospitable environment requires an extremely delicate adjustment. Its foothold is tenuous at best. In accordance with this, Miss Kol found that some of the minute plants could grow only on ice and others only on snow. They had no choice of habitat.

"The algae can hardly be said to live on pure ice or snow--if such things exist in nature. They are confined to the surface where minute particles falling from decomposing and shattered rock, and wind-carried dust dissolve slowly in the moisture more or less continuously present on the surface. This alters the chemical composition of the environment and provides the plants with the minerals essential for life. There are striking changes in type, Miss Kol found, depending on whether surrounding mountain slopes are acid or alkaline in their geochemical composition.

"The snow- and ice-plants presumably play an important role in the economy of life in the Far North and perhaps serve as the chief food for some other form of life which in turn supports higher forms. The life-cycle of the minute organisms remains unknown and the possibility of determining it for the present seems to have been ended by the loss of Miss Kol's living material.

"Among the types found was one which appears only as a purple 'bloom' on ice and another which makes isolated snow-fields the color of red pepper.

"Miss Kol also found on the snow-fields nests of 'snow-fleas'--minute lively little insects which find a tenuous habitat on dirty snow. They occur also on Canadian snow-fields and in Europe."--Washington News release.

The effects of snow-cover on depletion of fish-life were briefly mentioned in the Snow Report for 1941-42 [Transactions of 1942, p. 412] and the statement was made that "in the Western mountains where the snow is abnormally deep such mortality of fish is slight but here the lakes are deep and decaying vegetation scant," thus assuring a sufficient hold-over of oxygen throughout the winter.

A rare illustration of this fact is the school of large trout alert but contented in Lake Helen (8,400 feet) in Lassen National Park where in April, 1941, the snow-cover was 24 feet deep with a normal depth of at least 16 feet. This lake was only moderate in size and depth but was clear of vegetation.

Instrumental equipment

The year has seen a large advancement in instrumental equipment, stimulated by research projects in snow.

As previously mentioned, improvements have been effected in precipitation-gages, windshields, and snow-sampler, and a telethermoscope, calorimeter, and classification of snow- and ice-forms have been developed. A perfect dye has been discovered in Fuchsine for detecting moisture and tracing its movement in snow.

Most of these improvements have been described briefly and illustrated in the snow-study program at Donner Pass in the Central Sierra Nevada [see Transactions of 1943, Part III] at Corvallis, but a more detailed report is under way with further tests this coming winter.

The tests already made assure the general accuracy of open precipitation-cans against evaporation and their wider use where recorders cannot be provided, the easy reporting of snow-types and texture by cooperative observers, a recording precipitation-gage of capacity for one to six months depending upon the quantity of precipitation, a wind-shield that will withstand high wind, the accurate determination of the calories necessary to melt various types of snow, and the tracing of the movement of water in snow.

Snow-samplers

The cutter of the Mount Rose snow-sampler that in recent years had failed to penetrate frozen snow readily has now been restored to its original shape and temper manufacturers had attempted to increase its cutting faces and durability but the result was stubbiness, clogging of the cutting faces, and resistance to sharpening in the field. The divergence between the two cutters is shown in part in Figure 6. The frozen snow, unusual in the West but frequent in the East, afforded a welcome test. JOHN T. RYAN, who aided the inventor in the restoration, believes that he can develop a different type of cutter that will penetrate the snow even more readily than the original.

Fig. 6--Mount Rose snow-sampler cutter
(Preferred form shown on left)

To prevent the rapid loss of heat in the metal of the sampler-tube and thus avoid adhesion of snow to it, attempt has been made to procure an enamel or lacquer of low heat-conductivity. IRVING F. HAND for the Blue Hill - Mount Washington Snow-Project has proposed plastic, but primarily to observe the rise of the core in the tube. The problem would then become the attaching of couplings and cutter to the plastic tube. Only where the snow is deep would the couplings be necessary.

The cutting of lateral cores in the snow-studies at Crater Lake and the difficulty of detaching the complete core through lack of a back wall provided by the ground led R. A. WORK and associates to design the Crater Lake Lateral Snow-Sampler. This sampler has a flexible knife attached to the cutter so that the core can be cut at any predetermined depth and drawn up unimpaired. This attachment is particularly useful in vertical sampling when measurements are made from one crust to the next.

A plastic snow-tube

IRVING F. HAND [Bull. Amer. Met. Soc., March 1943] has just published the following description of his plastic snow-sampler used in the Blue Hill - Mount Washington Snow-Project.

"During the meetings of the Central Snow-Conference held at East Lansing, Michigan, on December 11 and 12, 1941, mention was made of the difficulty in obtaining metal for snow-tubes. The use of a plastic seemed feasible and upon receipt of a 24-inch length of transparent, 1-3/4-inch diameter 'Fibestos' tubing furnished gratis by the Plastics Department of the Monsanto Chemical Company of Springfield, Massachusetts, a standard cutting head made by the Instrument-Division, United States Weather Bureau, Washington, was inserted at one end of the tube and one side engraved in 1/4-inch gradations.

"ROBERT W. ELSNER used the snow-tube in early 1942 at Mt. Washington, New Hampshire, and reported that it was very satisfactory. It was used at Blue Hill Observatory for snow-measurements four times daily early in 1943.

"Aside from the greater availability of plastics at the present time, there are several other advantages such as light weight with ample strength, smoothness of bore permitting easy emptying, a very low coefficient of expansion, freedom from danger of placing moist hands on frosty metal, and transparency, which obviates the necessity of cutting slits in the side to determine the length of the snow-core. Scales may be calibrated so as to read densities directly, and in practically all other respects the tube may be utilized in the identical manner of a metal one. Some care should be exercised to avoid excessively high temperatures when storing, as this material begins to soften at slightly higher than 140°F.

"We do not claim that 'Fibestos' is the best plastic available, for this is the only substitute we have tried, but this material serves so well that we have listed some of its major characteristics.

"Characteristics of 'Fibestos,' a cellulose acetate plastic available in sheets, rods, tubes, and molding material. Characterized by toughness and strength, broad range of color, inherent finish, adaptability to high-speed injection molding. Limitations: Low heat-resistance (140°F-150°F).

"Properties of tubes

Type, thermoplastic
Molding qualities, excellent
Specific gravity, 1.27 to 1.37
Refractive index (ND), 1.49 to 1.50
Ultimate tensile strength, 5,000-11,000 lb./sq. in.
Bursting strength (Mullen), 50-500 lb./sq. in.
Compressive strength, 4,000-16,000 lb./sq. in.
Machining qualities, very good
Odor, none to slight
Taste, none
Effect of metal inserts, none
Effect of cold water, none

Color: Available in an extremely wide variety of transparent, translucent pastel and opaque colors, as well as in many mottles, pearls, and ornamental configurations."

A test should be made of the adequacy of plastic for snow-tubes of 10 to 20 feet in length. Its chief value would be its low heat-conductivity, which should reduce the cohesion of snow rather than its value in preventing the sticking of moist hands to the metal, for in cold weather mittens are worn even for recording.

In all except the shortest tubes slits must be used for breaking up and removing the core. Inserting a rod from the end would pack rather than dislodge the snow.

Precipitation-gages

Clogging of orifices--When the sky is overcast and deposits of frozen fog and snow are unimpeded, there is real danger of clogging the throats of precipitation-gages, but where storm and intermittent sunshine prevail, the snow-caps are soon warmed by solar radiation and splash into the can.

The color of the metal also is a factor in the melting and opportunity for testing is available at Donner Summit, where the metals vary from gray to copper and black with the heated Stevens Type-W gage as a standard of comparison. The following test with beehives is valuable.

The effect of white in reducing the temperature of beehives in summer [Du Pont Agric. News Letter, May-June, 1943, p. 37] has been found to be "as much as 5°6, 6°8, and 8°8 F on different days in carefully controlled Canadian tests with hives located in the Sun. Tests were conducted by the Department of Entomology, the University of Manitoba, Winnipeg, during three different summers to determine the effect of different colored hive-covers on temperature within the hives."

Freezing of contents--Except under conditions of extreme cold or dilution, calcium chloride will maintain the contents of the precipitation-gages in the form of slush, which will be sufficient ultimately to change the accumulating snow to water.

The fluidity of the contents can be maintained or restored best by keeping the cans exposed to the Sun. Cans having a single wall and free from insulation by snow are most efficient, whereas cans with a double wall possess the thermos quality of preventing quick freezing but likewise preventing ready thawing after freezing finally has occurred.

Dark color should accelerate thawing, but gray seems to have been chosen as a universal color possibly because most gages are installed in warm areas where evaporation must be held to a minimum. The use of dark color on the case and a coating of oil on the contents might be a satisfactory compromise.

Distortion of record by drift-snow--This danger in the Sierra Nevada is not so great as feared but should be guarded against where the cans are low and the sweep of the wind unobstructed.

At Soda Springs the two precipitation-gages that were lowest and nearly engulfed by the rising snow-cover showed a suspicious excess in catch and a series of cups were attached to a pole to determine the relative catch of drift-snow at intervals above the snow-surface. But even after the snow-cover shrank, these gages continued to show an excess, though slighter, suggesting that the wind nearer the ground might be slower and the catch more accurate. The study will be continued but field-anemometers also will be employed.

Monthly totals so far obtained are given in the accompanying Table 3 as a basis for discussion.

Table 3--Monthly totals

Month	Gage No. 6 (17 feet high)	Gage No. 9 (10 feet high)	Gage No. 10 (10 feet high)
	inch	inch	inch
January	18.96	17.80	18.075
February	4.75	5.47	5.31
March	9.545	10.545	10.425
April	3.87	4.09	4.15
May	2.23	2.37	2.39

At Tahoe City the forest encircles the precipitation-gage so closely that continuous observation after storms has been inaugurated to determine whether the snow in the tree-tops drifts into the can. The results thus far are negative but observations will be intensified during high wind when the snow burden seems to leap from tree to tree.

The Alaska Project--The vicissitudes and hopes of the pioneer storage-gages in the mountains of Alaska described in the last annual report of the Committee on Snow [Trans. Amer. Geophys. Union, 1942, pp. 443-446] are briefly sketched in the following letter from ASHTON R. CODD:

"Your letter regarding the article on the storage snow-gages in Alaska was a pleasant surprise. I did not expect to see the paper printed but am glad that you have found space for it in the Transactions.

"The gages in Alaska have worked fairly well. At least we have caught some water. The shields on the gages at Juneau did not stand the terrific winds but those at Ketchikan worked out fine. Those at Juneau seemed to be exposed to the Taku winds that sweep off the glacier to the coast and are very strong. Some winter pictures I received from the men at Juneau were very discouraging. They showed rim-ice 12 inches thick over the tower and the shield in such a condition that you just shake your head. However they reported that the throats of the gages were clear and the resulting catch encouraging. The shield-leaves were completely blown away. From a later report it appears the rivets on the shield-supports were not securely fastened and the chain at the bottom is too light. These two items can be corrected and we are going to try again."

Polar Regions

Expeditions--The mastery of the Polar Regions has now been assured by the traverses with stops at will of the Antarctic Plateau by LINCOLN ELLSWORTH in 1935 and the Arctic Ocean by IVAN CHEREVICHNY in 1941.

The story of Ellsworth's achievement and its significance has recently been published in "American Antarctic discoveries, 1819-1940" by WILLIAM HERBERT HOBBS [Proc. 8th Amer. Sci. Cong., Washington, D.C., 1940, pp. 47-54].

The details of "Ivan Cherevichny's Arctic Flight, 1941" were published by Professor N. ZUBOV [Anglo-Soviet J., 1942, pp. 48-51, 1942] and have been summarized in Polar Record of July 1942 [pp. 564-565]. As compared with the drift of the Fram, the Maude, and the Sedov, and the North Polar ice-pan of Papanin, Cherevichny's was a mobile, speedy expedition. From March 5 to May 11 the Arctic Sea was traversed from Archangel to Wrangel Island near Bering Strait and three landings of 3-1/2 to 6 days each were made on the ice in the "blind spot" between Wrangel Island and the North Pole.

"The points of these three landings form an almost equilateral triangle and thus the expedition's observations covered a large area in one of the least-known parts of the Arctic Ocean. Soundings showed that the depths were about half that of the single sounding of 5,419 meters made in 1927 by Sir HUBERT WILKINS in the same general area. The depths measured by Cherevichny were 2,647 meters at the first station, 1,856 meters at the second, and 3,430 meters at the third. The warm Atlantic waters discovered in the intermediate layers of the Arctic Basin by Nansen, Papanin, and the Sedov Expedition were found to be extremely pronounced in the region of the 'Cherevichny Triangle.'

"The positions of the three stations have enabled an estimate to be made of the direction and speed of movement of the ice. During the first three days that the expedition spent on the N-1 ice-floe it drifted almost 50 km north. While the aeroplane was on the N-3 ice-floe it was carried almost 40 km south-southeast. The N-1 ice-floe was 196 cm thick. It is known that floes of this thickness form in one winter in the northern parts of the Kara and Laptev seas. It is also known that the ice-field on which Papanin's party landed at the North Pole in 1937 was three meters thick. It is not yet possible to deduce the origin of the ice in the region visited by the 1941 expedition."

Cherevichny, in addition to his companion, V. AKKURATOV, was accompanied by three scientists, namely, Director LIBIN of the Arctic Institute, the hydrologist N. CHERNIGOVSKY, and the physicist M. OSTREKIN. Observations were made in hydrology, meteorology, geomagnetism, gravity, and the drift of the sea-ice.

"The route of the return flight was approximately the same as that of the outward journey, and the same observers were therefore able to record the changes in ice-conditions which had taken place during the previous six weeks."

Quoting also from Polar Record (foreword of January 1943): "Everyone interested in the history of the Arctic will have noted that last year saw the accomplishment of the first west-to-east successful navigation of the Northwest Passage.

"The auxiliary schooner, St. Roch, manned by eight members of the Royal Canadian Mounted Police, reached Sydney, Nova Scotia, on October 9 last year after a 28-month voyage from Vancouver via the Arctic.

"After centuries of effort, the first successful navigation through the Northwest Passage from east-to-west was made in 1903-05 by ROALD AMUNDSEN in the Gjöa. No other ship has passed right through, although the Nascopie from the Atlantic and the Aklavik from the Pacific met in Bellot Strait in 1937 and again at Fort Ross in 1938. Few attempts at the west-to-east route have been made.

"The voyage of the Gjöa appears to have been of longer duration than that now completed by the St. Roch, but it will be remembered that one of Amundsen's principal objects was to take magnetic observations, and he deliberately spent two winters at King William Island."

Anti-frostbite precaution--At the present time when war has spread even into the Arctic the following summary on anti-frostbite ointments by BRIAN ROBERTS [Polar Record, pp. 30-31, January, 1943] seems appropriates:

"To summarize: It is inadvisable to wash the face or shave just before going out into a very cold, windy environment, as this removes the natural oils from the skin. Before any prolonged period of exposure olive oil or animal fat may be rubbed into the exposed areas of the skin as a preventive of frostbite. No form of irritant should be used to increase blood circulation."

Snow-caves--One who has lived in a tent on the polar ice will appreciate the igloo of snow-blocks or a snow-cave if they can be produced from available snow. The snow-cave is normal among Eskimo of the Hudson Bay Region [see Rasmussen, Across Arctic America] and was used for a year at Eismitte by the Wegener Greenland Expedition.

The following note [Polar Record, pp. 26-27, January, 1943] is reproduced because of the simplicity of the method and the trend toward overnight ski-trips.

"Snow-caves: (In The Canterbury Mountaineer of Canterbury, New Zealand, for August 1941 [pp. 83-85] R. LOGAN gives some notes on the use of snow-caves in providing adequate shelter and reasonably comfortable quarters for prolonged assaults on some of the higher peaks in New Zealand. This method was used with great success on Kangchenjunga by PAUL BAUER [see Himalayan Campaign, Oxford, 1937]. A knowledge of how to excavate snow-caves should clearly form part of the normal technique of polar travellers.)

"The equipment needed is simple: Two household coal shovels, a square of waterproof material for a door, and some sheets of pitch-centered heavy brown paper for the cupboards and possibly as an effective floor-covering. Logan's caves were about five feet high, nine feet long, and eight feet wide. With two men on the job a cave of these dimensions can be cut in two to three hours. The best method is roughly as follows: When a suitable site has been selected, on a reasonably steep slope (with due regard to avalanche-danger), a working shelf is cut into the slope, and then a small cave two feet by one and one-half feet is excavated back for a foot or two. This is the doorway. The cave proper is then started, and it is awkward work in the confined space until there is standing room. After this, progress is easy and rapid, the best procedure being to cut the snow out in blocks, which are thrown out of the door and down the slope. The ceiling should be shaped as a Gothic arch, to allow any condensation to run down the walls; a refuse pit in one corner solves the garbage problem.

"The cave appears to offer many advantages over the tent. Once occupied, the air-temperature in a cave rises to a degree or two above freezing-point, and remains at this temperature until the cave is vacated. Water left in a billy on the floor overnight does not freeze; boots similarly treated remain pliable. The two main advantages, however, are adequate accommodation and complete shelter. Adding extra room and making small improvements provide useful recreation and interest on days of blizzard, varying the monotony of inaction. With head-room sufficient to walk about, the usual cramping confusion of a tent is avoided; cooking may be done standing in a large recess, and whatever the weather outside, the party in the cave, with the doorway closed up, is perfectly immune in tranquil surroundings. A blizzard can do its worst without in any way affecting the comfort, safety, or morale of the party.

"Intending cave-dwellers need not be alarmed when daylight filtering through the ceiling makes it look as though it will collapse at a touch. Everything will be under control provided there is not a big thaw. Even 18 inches of snow at the peak of a Gothic arch will hold two men standing on it. No artificial light is needed inside in the daytime, and owing to reflection, a single candle gives good illumination at night. Everything should be taken into the cave as soon as it is occupied, especially the shovels."

Transport

Highway snow-removal--The clearing of our highways from snow-accumulation in winter will remain the basic problem of transport of heavy materials, although motor-sleds and airplanes will carry the lighter and faster loads.

In an editorial, "Fantasy of the Far North" [Eng. News-Record, June 3, 1943], offers an "Alcan Elevated supported by skyhooks" in reply to the suggestion of Secretary of Interior HAROLD L. ICKES that the Alaska Highway be elevated to avoid "trouble with snow and ice and bogs and all that sort of thing." Naturally elevation will not eliminate all such troubles and may even accentuate them. In reality the snow in the Far North is not deep though it may drift.

The efficiency of snow-removal and its extent irrespective of topography is stressed by T. H. DENNIS, State Maintenance Engineer, California Division of Highways [Pacific Road Builder and Eng. Rev., October 1942]:

"California Division of Highways spends $500,000 annually to remove snow on some 3,750 miles, or 27 per cent of its State highway-system. This is not surprising if you glance at a relief-map of the State. You will find its main valleys almost entirely encompassed by mountain ranges, those on the east reaching elevations varying from 4,000 to well over 8,000 feet. It is only in the south and southeastern portions that the traveler entering the State during the winter is not at some point in his journey treated to vistas of snow-clad peaks and hills.

"In normal times snow-removal is effected on major routes carrying important inter- and intra-State traffic as well as on roads serving isolated communities. This service, to a limited degree has likewise been extended to certain recreational routes offering special advantages in snow-sports. Justification of such consideration, in a measure, rests in the $15,000,000 which its devotees estimate is spent annually on these sports and related activities. Obviously peace-time policies should now undergo such changes as may be required to conform with the government's expressed desire that rubber, manpower, and equipment be conserved and that snow-removal service be restricted to those roads which are vital to the war effort.

"Present day snow-removal operations have now reached a point of efficiency, due to the improvement of equipment and planning, whereby traffic may in general schedule their trips over even the highest passes. The installation and operation of radio equipment between plows and land stations likewise insures traffic against hazardous and tedious tie-ups when storms prove too heavy for immediate handling.

"The equipment-shelter accommodates eight pieces of equipment with an additional space, segregated from the main storage, which is reserved for making equipment repairs. Heat, lights, and hot water are carried to both housing quarters from a boiler-house sufficiently removed to eliminate the hazard of fire. Similar precautions are observed in the placement of the oil-and-gas house, as the destruction of either major housing unit would jeopardize if not conclude the entire winter's operation."

During the past winter snow-removal equipment was concentrated on the military highways but the small mountain towns were provided with far better outlet than was usual a decade ago.

Montreal and adjoining towns at the beginning of winter feared that they would be unable to clear streets and sidewalks as formerly due to inability to obtain proper working forces.

Engineering News-Record, as an essential service, provides "Manufacturers' announcements of snow-handling machines" [November 5, 1942, pp. 117-128].

Snow-fences--Associated with snow-control are the fences built or planted along the highways to prevent congestion of snow in the path of travel. Supplementing the paragraph on snow-drift control [Trans. Amer. Geophys. Union, p. 431, 1942], M. W. TORKELSON, Director of Regional Planning, Wisconsin State Planning Board, points out [Eng. News-Record, September 24, 1942, pp. 58-59] that the earliest attempt to control drifting by means of plantings, of which he has knowledge, was carried out by the Wisconsin State Experimental Farm at Hancock about 1930 and that a roadside-planting project was begun in Wisconsin in 1932. Despite drought the pine trees in their third year were quite effective in trapping drifting snow and keeping it off the highway. After five years' additional growth, this double hedge was quite the master of a heavy snowfall accompanied by severe drifting, which took place on January 14, 1940. "There was much more snow on the south side of the planting than on the south side of the adjoining lath-and-wire snow-fence."

Director Torkelson continues: "Of interest are the volunteer growths of willow which have sprung up along the roadside since the project was graded. In this State and probably throughout the Middle West, such volunteer growths assert themselves quite soon and within ten or fifteen

Fig. 7--Standard snow-drift fence on Bonneville Salt Flats, Wendover, Utah

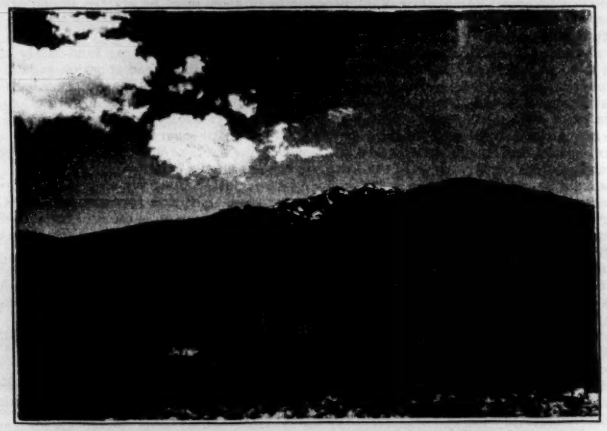


Fig. 8--Snow-drift fence of sagebrush, Wells, Nevada (Ruby Mountains in distance)

years provide a job of roadside improvement which in my opinion is equal to, if not better than, most plantings. If the grading is done in such a way that the volunteer growths do not have to be disturbed, they will help to reduce the expense of plantings.

"Within the last few years hundreds of miles of pine windbreaks have been planted, in some cases to control drifts along highways but in most cases to conserve soil-moisture. The value of such plantings is very great, and it seems that the work will continue on an even greater scale as its value both to agriculture and to highway maintenance is more widely appreciated."

In the far West where sagebrush and juniper are available on the spot, primitive but even more efficient fences of these materials are taking the place of the slat-fences. The brush is held in place by being hung downward from wires strung on posts. The value of the plantings and the brush is their more complete atomizing and neutralizing of air-currents (see Figs. 7 and 8).

Snow-removal from airports--Indicative of the challenge of snow in airport operation, is the article on snow-removal from airports, "Fighting snow to keep 'em flying" by HAL W. HUNT [Eng. News-Record, November 5, 1942]. The article is a compendium of practice interspersed with the physics of snow. (A reprint of this article, together with the description of snow-handling machines can be obtained from the editorial offices of Engineering News-Record, New York, for ten cents.)

"Clearing snow from airports assumes unusual importance this year as many new fields face their first test of winter operation. Heretofore, under extreme conditions, flying could be suspended, but this winter the runways must be kept continuously open to be ready for offensive or defensive action and to keep the pilot-training program in full operation. To assist in this essential part of the war effort, airport managers, airline officials, equipment-manufacturers, and representatives of the United States and Canadian governments were questioned as to practices that they recommend for effective, economical and efficient snow-removal.

"The results of this survey are presented here for such value as they may have in keeping military and civilian airports in service through this vital winter.

"Briefly, the consensus is that the one desirable method of handling snow on airports is to get it off, and keep it off, the runways at all times. In some places this is not practicable, and other means are employed, but complete removal of the snow is always desirable, as the one safe landing-area for an airplane is a clean and clearly defined runway.

"The machines available, the expected rate and duration of snowfall and whether the snow is fluffy and dry, govern the time snow-removal should start. Weather reports should be carefully studied so that personnel will be on hand when needed and so that plans can be made for clearing snow from the runways that lie in the direction of the wind as soon as the snow becomes deep enough to be troublesome. Removal or other processing of snow must be started in conformity with the storm and continued until the snow is under control without regard to shifts or two 40-hour-week limitations.

"If the snow is dry and fluffy, and not drifting, a transport-type plane can land safely in as much as six to eight inches of snow. This amount will not retard the speed at which snow-removal units may operate, nor will it be a menace to operation of moderate sized planes, as in emergencies they have landed in 18 inches of soft snow. If the snow is moist and the expected fall is heavy, removal should start when the depth is only two or three inches, to avoid building up to greater depths before clearing can be completed. Aircraft equipped with high-pressure tires are capable of operating from airports having considerably more soft snow on the surface than can planes equipped with airwheels due to the larger tire-area of the latter and the resulting greater resistance.

"Snow should be cleared as close to the surface as possible. Along the seacoast, however, ice may be expected to form from packed snow, sleet, or from light rain freezing as it falls.

"Rather than clearing ice by mechanical means, abrasive material is often used to skidproof the affected areas. Sand is a preferred means but if hot the particles embed themselves in the surface and thus resist propellor-blasts and wind.

"Although commercial airlines have not generally favored the use of chemicals, which have a tendency to cause oxidation and rusting when splashed on the planes, the Civil Aeronautics Authority and the Army Air-Force authorize the use of calcium or sodium chloride for clearing runways of ice on airports under their jurisdiction.

"The average snowfall over a period of years is not a safe indication of the snow-handling problem. In an area indicated as having 80 inches of annual snowfall, 21 inches of snow fell in 22 hours last winter.

"In colder climates or at airports which must accommodate ski- as well as wheel-planes, or seek to reduce snow-clearing costs, a technique of rolling and consolidating snow for landing-surface has been developed.

"Such surfaces can be maintained reasonably well away from the coast where the snow is fairly damp when it falls and yet temperatures are consistently low. In coastal areas where rainfall may occur and the snow is wet and slushy, it will be found difficult, if not impossible, to maintain snow-surfaces, and removal of the snow will be found the only alternative.

"Only a moist snow can be successfully compacted into a really good runway-surface. Dry and sandy snow cannot be packed with any degree of safety. It may be possible to develop a substantial crust on the surface which appears to be able to support large aircraft, yet it will be found that flaws and soft spots will almost always remain which constitute a menace to landing aircraft. In the case of oil-spots, the dark color absorbs heat from the Sun and causes a soft spot below. Dry, fluffy snow is practically impossible to pack, and it will be found necessary to remove such snow from the runways until suitable snow falls. When the season, temperature, and probable fall of snow indicate that a time has been reached that a snow-surface can be maintained, rolling should be started.

"A properly compacted surface does not usually honeycomb during the period of the spring thaw, like ice on a lake, provided it is properly worked during the thawing period. Such compaction should usually be done in the late afternoon so that the surface will be smooth before it refreezes

during the night. Particular attention should be paid to temperature-forecasts as there will be times when the temperature will remain above freezing through the night and no work should be done on the ports at such times.

"By keeping the whole surface of the airport smooth, it will be found that under high-wind conditions certain falls of snow will be carried entirely off the field. Also, the evaporation of snow under the Sun's direct rays is greater and will be more even if the entire surface is smooth. For this reason, if time permits, the whole of the airport surface should be rolled and dragged.

"At Russian airports, rollers are preceded by drag-units to level the snow. 'Sheepsfoot' rollers are also employed apparently to aid compaction. Above 21°F snow is very likely to adhere to the rollers. A coating of shellac helps greatly in preventing adhesion. Another effective method is to use a saline solution applied to the rollers while in operation.

"The plan is not to attempt to remove the snow at any time during the winter, but to compact successive snowfalls so that planes land on a paving of snow or what may eventually become ice. The surface may thus be continuously raised throughout the period of snowfall. The depth of snow will be lowered somewhat throughout the winter as some is carried away by the wind and evaporated through the action of the Sun's rays even during the coldest weather."

In Alaska, as contrasted with Canada, "dragging with the proper equipment has proven the most efficient method of field-maintenance, with the exception of actual snow-removal."

Ice-breakers--Quoting from the Engineering News-Record [March 18, 1943], "In the light of experience gained this winter in keeping the Illinois Waterway open with ice-breakers, early opening of the upper Mississippi River Waterway is to be attempted this year to help ease the transportation load on the railroads serving that part of the country. It is hoped to advance the usual opening several weeks. Between Dubuque, Iowa, and St. Paul, there are ten locks and dams that are expected to complicate the job of the ice-breakers. A large convoy of barges now assembled at Alton are loaded with coal and oil and will return with grain and raw materials."

Motor-sleds--Of the various types of motor-sleds, the caterpillar-type still gives greatest satisfaction under all conditions of snow. The public service companies particularly desire a heavy-duty sled capable of carrying linemen and equipment wherever power- and communication-systems extend. The "Sno-Motor" [Trans. Amer. Geophys. Union, p. 971, 1941] has been commended.

The Tucker "Sno-Cat" [Trans. Amer. Geophys. Union, p. 425, 1942] is being reproduced in limited quantities for test by the military service but should be further adjusted before it can rival the jeep in efficiency.

The "Motor-toboggan" [Trans. Amer. Geophys. Union, p. 973, 1941] has been tried by J. C. MARR in the mountains of Idaho but found too dependent upon the texture of the snow. The "Snow-plane" [Trans. Amer. Geophys. Union, p. 427, 1942] suffered accident. The Division of Irrigation in charge of snow-surveys has therefore turned to the helicopter as reliable whatever the ruggedness of the slopes and the depth of the snow.

Icing of airplanes--I. Imai in an article on "Physik der Vereisung an Flugzeugen" [Snow and Ice (Japanese), September 1941, pp. 7-9] seeks to advance the physics of the icing of airplanes, the knowledge of which he feels is not yet complete.

Among other steps, he notes that "(1) icing occurs in every cloud at temperatures below 0°C that consists not only of supercooled water-drops but often also of snow-crystals or ice-particles. It appears, however, after our observations organized on mountain tops that the latter can have no share in the icing."

Table 4

Air-temperature	Wind-velocity	
	10 m/s	30 m/s
- 1°C	0.07	0.18
- 5	0.40	0.94
-10	1.76	1.8

"(6) The speed of growth of ice in hoar-frost is approximately $\alpha v w$ (that is, a number between 0 and 1, designated accumulation-capacity × wind-velocity × water-content of cloud) whereas that in hoar-ice, independent of density and size of drops of the cloud, is determined by air-temperature and wind-velocity, as in Table 4 (in cm/hr).

"These values are somewhat smaller than appear in literature."

The deicing of airplane-wings has now become automatic through use of an electronic instrument that sets the deicers in motion whenever the ice forms.

In this connection, the following item from The Frontier of June, 1943, is included as supplementing or illustrating the invention of RUSSELL S. COLLEY [Trans. Amer. Geophys. Union, p. 968, 1941]:

"Airplane-wing slots protected from ice-accumulation: A set of inflatable rubber 'shoes,' designed to prevent the accumulation of ice in the vicinity of airplane-wing slots, has recently been patented. This ingenious device, illustrated below (Fig. 9), is said to increase rather than decrease the lifting effect of the wing and reduces stalling speed. Two separate shoes, (A) on the leading edge of the wing and (B) on the rear wall of the slot, are fastened into hollow rivets (C) on the skin surface. When the shoes are inflated, bulbous distentions (D,E) increase wing-camber and extend the opposite walls of the slot (F) downward, increasing effective slot passage and the resulting lift-drag ratio."

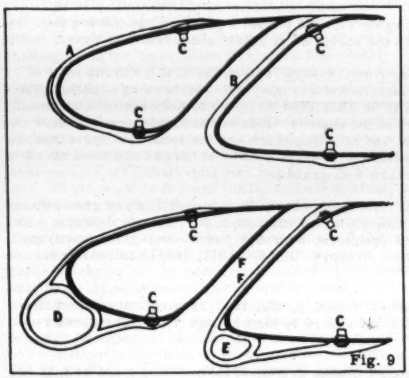


Fig. 9

Winter warfare--When the war is ended the story of achievement and heroism on the part of investigators of snow will be released with its wealth of technical material.

The press affords us glimpses. Among these are: "Below-zero test for armaments" at Shiloh, Manitoba, hundreds of miles from the United States - Canadian border; "How troops train for mountain war--high in the Rockies, the hardest kind of battles;" "Skiing scout gets Japanese" on Attu, but this scout slid on a canvas-toboggan past the foxhole to drop his grenade; "Veterans of the Guadalcanal battle waded hip-deep in mud and armpit-deep in snow on Attu and swore that its mountains would make South Pacific fighting look like a picnic;" "Wrecked U. S. fliers live five months in Greenland: No heat, light, little food."

The last tale, by REUEL MOORE, comes close home to the Committee on Snow because of its participants, BERNT BALCHEN of Antarctic fame, MAX DEMOREST of the International Commission of Snow and Glaciers, and the Iceberg Patrol Steamer Northland, and will be retold in full.

"Washington, May 3 (U.P.)--One of the most remarkable rescue stories of the war--how seven of nine army fliers were saved five months after their Flying Fortress crashed in northern Greenland--was unfolded today as three of the adventurers gave President ROOSEVELT a first-hand report.

"During the ordeal, two of the bomber's crew and three would-be rescuers perished in the arctic winter weather. Three others attempting to reach the scene were also lost.

"The Fortress, sent out last November in search of the crew of another plane forced down, crashed November 6 on the ice-cap on the west coast of Greenland.

"Colonel BERNT BALCHEN, noted arctic explorer and hero of two previous rescues in the far north, spotted the wrecked plane soon after the crash and dropped supplies to the crew. Five months later, on April 6, he flew in a giant navy patrol bomber to bring out the last of the survivors.

"Captain ARMAND L. MONTEVERDE, Annaheim, California, the pilot, Lieutenant HARRY E. SPENCER, Jr., Dallas, co-pilot, and Sergeant DON TETLEY, San Antonio, Texas, called at the White House today to tell Mr. ROOSEVELT of their experiences. They were accompanied by General HENRY N. ARNOLD, Commander of the Army Air Forces.

"The bomber broke in two and its radio was wrecked in the crash. One of the crew members, Sergeant PAUL J. SPINA of Frankford, New York, was thrown clear, but one arm was broken. Others were shaken up, cut and bruised, but none seriously injured.

"Monteverde, using experience gained as a Boy Scout, set Spina's broken arm and directed preparation for a makeshift shelter--in the tail of the wrecked bomber.

"There were only limited rations, no heat, no light. For ten days, the weather was extremely severe, and high winds and driving snow prevented any of the party from leaving the plane.

"Corporal LOREN E. HOWARTH of La Crosse, Wisconsin, finally managed to move the damaged radio into the navigator's compartment, got it operating, and contacted the outside world. The Army, Navy, and Coast Guard joined in the rescue efforts and Balchen, on the 15th day, dropped supplies a few miles from the scene.

"Lieutenant MAX H. DEMOREST, Flint, Michigan, and Tetley, stationed at a weather outpost near the crash-scene, set out by bomber-sled to effect the rescue. They had to abandon the sled some distance from the wrecked plane, but fought through drifts on foot to reach the stranded men.

"They returned to the weather station for other sleds but on the return trip Demorest disappeared in a crevasse less than 100 yards from the plane.

"Meanwhile, a Grumman Coast Guard plane piloted by Lieutenant JOHN A. PRITCHARD, Burbank, California, from the Coast Guard Cutter Northland, landed less than a mile from the wrecked plane. He flew back to the Northland with the first two men to be rescued.

"He returned to the scene, and took off again with Howarth as a passenger. Fog closed in and the Grumman crashed. Pritchard, Howarth, and Pritchard's radioman, BENJAMIN O. BOTTOMS of Salem, Massachusetts, were killed.

"Meanwhile, Lieutenant WILLIAM F. O'HARA of Scranton, Pennsylvania, Monteverde's navigator, was seriously ill. His foot had been frozen and gangrene set in.

"Monteverde put him on Tetley's sled and instructed his two strongest men, Spencer and Private CLARENCE WEDEL of Canton, Kansas, to accompany them. They had gone only a mile when Wedel fell through the snow into a bottomless crevasse.

"Four miles further on, the motor-sled broke down. The men were now separated into two marooned camps. Bad weather and virtually impassable terrain frustrated efforts to reach them, but the Air-Transport Command kept them alive with supplies dropped.

"In February, Colonel Balchen with a Navy crew landed a PYB in deep snow beside the sled-camp and succeeded in taking off with the four marooned men.

"Bad weather prevented his return until early April when he flew to the sled-camp again and landed a dog-team and a number of rescuers. After several days' delay by bad weather the rescue party reached the wrecked Fortress and returned to the sled-camp with Monteverde, and Spina and Sergeant ALFRED BEST of Waco, Texas

"Balchen made his third remarkable landing successfully April 6 and returned with the balance of the Fortress crew and rescuers.

"O'Hara lost both feet. All others have recovered completely.

"Monteverde and Spencer are returning at their own request to the Air-Transport Command."

"Fourteen days of hell on an ice-cap" by C. B. WALL (Readers Digest, June, 1943) reveals unusual snow-conditions on the Greenland coastal ice-cap and human resiliency under desperate conditions. It belongs with "Prisoner of the sand" in "Wind, sand, and stars" by ANTOINE de SAINT EXUPÉRY as a vivid nature picture and marvelous escape.

At this same latitude (the Arctic Circle) and likewise in winter but 100 miles inland behind the barrier range the Chairman (J. E. Church) found scant snow on the ice but ruinous downslope gales.

The inner self of the snow scientist is revealed in a letter written at Edinburgh on April 24, 1943, by Major E. A. M. WEDDERBURN, member of the British group of the International Commission of Snow and Glaciers, who was invited to speak on snow-transport at the annual meeting in 1943, which is quoted:

"I have been moving around a good deal recently but am now back for a bit and was delighted to get your letter written at the beginning of March which had been held for me. Alas, today is one of the days of the American Geophysical Union Annual Meeting and I am some thousands of miles away. But you are very much in my thoughts and my best wishes are with you as I write.

"Even had I been in Washington today I fear that I would have been unable to read the paper we had planned. The subject has become one of considerable military importance and until after the war no open discussion of it will be possible.

"Although I never knew him I am sad at the loss of MAX DEMOREST in the field and I shall look forward to reading an appreciation of his work.

"In Britain we have had one of the most snowless winters on record and what work we had planned to do here could not be carried out. I understand, however, that important results in the field I am interested in were obtained in the United States of America and Canada though I have not yet received details.

"I am sad to hear that even Soda Springs has not escaped the war. I have the very happiest memories of it and I hope it will be my good fortune to revisit it and Reno one day. But such nostalgic thoughts are rather out of place at present for we have what is obviously going to be a long hard task in front of us but one which is going to be tremendously worth while.

"It is extremely pleasant to me to hear from you and to be thus kept in touch with my old interests. I hope that before long there will be another Congress in Europe at which, if asked, I will be happy to read a paper in lighter vein, for example, 'Wanderings of a snow warrior' or something of that sort."

Snow-sports

Snow-sports, originally considered as a sustainer of morale, have been greatly curtailed by the stress of war.

At the beginning of winter R. H. BALDOCK, engineer for the Oregon State Highway Commission, announced that "none of Oregon's famous scenic highways would be kept open for scenic purposes. Shortage of funds and heavy military demands for snow-removal necessitated the new policy."

Likewise California concentrated its snow-removal equipment on military highways that must be kept open constantly. "We cannot afford to operate snow-plows on mountain highways and then be compelled to remove this equipment on a moment's notice, leaving recreationists stalled on partly cleared roads during a storm. We would only jeopardize lives and the war effort by doing so," said Maintenance Engineer T. H. DENNIS.

Consequently snow-sports were restricted mainly to the military highways and waned even there because of the rationing of gasoline and restrictions imposed by rail and bus lines. The Snow Sports Bulletin by the United States Weather Bureau was, however, issued throughout the winter.

The travel to National Parks has fallen off greatly. In Yellowstone Park in 1942 the season's travel was only 29 per cent of the previous year. However, all of the parks will be open the present season for visitors as usual, although the personnel will be curtailed. "Food and lodging will be available for whoever can get there."

National Park pride is expressed in the following correspondence regarding the location of greatest snow-depths:

HAROLD CONKLING to J. E. CHURCH--"We have a letter from JAMES V. LLOYD, Superintendent of the Lassen Volcanic National Park, Mineral, California, from which we quote: 'It is understood that greater depths of snow are recorded for the Lake Helen Basin than anywhere else in North America. Do you have data on snow-depths elsewhere that equal or exceed those of our area?'

"Attached is a copy of our answer to Mr. Lloyd. Do you have any additional information as regards greater depths of snow actually measured at any other location? If you have it would be appreciated if you would so advise Mr. Lloyd."

HAROLD CONKLING to JAMES V. LLOYD--"Insofar as the records of our snow-surveys are concerned they show that greater depths of snow have been recorded for the Lake Helen Basin than for anywhere else in California.

"The measurement of April 8, 1941, of 287.1 inches of snow and 134.5 inches of water is the greatest snow-depth measurement of record. However, the March 31 measurement of 1938 showed a heavier snowpack. The depth was 282.4 inches and contained 152.5 inches of water.

"We do not know of any records showing a heavier snowpack anywhere else in North America, but there has been some controversy connected with this, as the rangers in Washington claim that had they made a measurement at a certain place at a certain time it would have shown a greater depth than that recorded at Mt. Lassen. However, this is highly hypothetical and we do not know whether they have ever been able to substantiate their claims by actual measurements. Dr. Church of the University of Nevada may know something more about this and we are asking him if he will tell you what he knows about it.

"The discrepancy between the average figures for 1943 for Mt. Lassen as computed in your office and in ours is probably due to a slight difference in our methods of computation. Whereas this office averages the upper and lower courses independently and takes a mean of these averages as representing the average for the area, it would seem that your office has taken a straight average of the combined samples of both snow-courses. The attached memorandum prepared by Mr. Paget will make this clear."

JAMES V. LLOYD to J. E. CHURCH--"Your courtesy in supplying this office with information concerning snow-depths is deeply appreciated. We were glad to know definitely that the measurements at Lake Helen are the greatest that have yet been recorded. We shall continue to express our pride in the snow-depths recorded at Lassen Volcanic National Park until they are surpassed."

The location of the potential maximum snow-cover is on Mount Rainier or farther north. The final decision must depend upon high-level snow-surveys on mountains, such as Mount Fairweather, of the South Alaska Area [Trans. Amer. Geophys. Union, pp. 962-963, 1941: also Hydrology, Physics-of-the-Earth series IX, pp. 89-93].

Snow-perils and avalanches and new avalanche institute

Swiss leadership--Continuing the research of recent years is the new Research Institute of the Swiss Snow-and-Avalanche Investigation Commission on the Weissfluhjoch above Davos, Switzerland.

The news is conveyed in an article from the Schweizer. Bauzeitung, of June 27, 1942, "Neues Forschungsinstitut auf dem Weissfluhjoch der Schweiz. Schnee und Lawinenforschungs-Kommission, by ROBERT HAEFELI, who has frequently reported the activities of the Weissfluhjoch Station since 1934 and has now presented a report for 1934-40, in French and German [Intersylva, Organe du Centre International de Sylviculutre, v. 1, 1941, Berlin]. The substance of the latter has appeared in Transactions of the Union [pp. 393-395, 1940, and p. 978, 1941], the former appears below.

From 1876 till 1938 in Switzerland for afforestation and avalanche-prevention 48.5 million francs have been expended exclusive of the costly maintenance of structures and the erection of numerous galleries for the protection of roads and streets. With the increase in Alpine winter traffic and the extension of Alpine roads the solution of all the technical problems connected with the snow-cover steadily became more pressing. This led in 1931 to the founding of the Swiss Commission for the Investigation of Snow and Avalanches.

A gradual development soon brought the realization that to meet the various phases of the problem close cooperation must be established with other organizations. These were the Federal Inspection for Forestry, Minerological-Petrographic Institute of the Federal Technical High School, Underground Division of the Experiment Station for Hydraulics of the Technical High School, and the Physical Meteorological Observatory at Davos. Finally the division of Hydrology now associated with the Station for Hydraulics was drawn into the cooperation.

After several years of preliminary investigation and observation in different sections of Switzerland, but particularly at Davos, a provisional laboratory was set up on Weissfluhjoch, that is, at the source of avalanches. This laboratory consisting of a wooden barracks can no longer meet the requirements of the experiences accumulated during the first ten years.

The choice of location could not have been more favorable for the following reasons: (1) Location is between 2,000 and 3,000 meters, that is, in the midst of the principal source of avalanches and also in the center of Alpine winter traffic. (2) Rail-connection is available with the valley station of Davos during the main season of December to April, as also good connection with Zurich, seat of the Federal Technical High School, and telephone. (3) It is an easily accessible area for the carrying out of field-studies with various exposures essential for the formation of avalanches and a neighborhood of avalanche-barricades, comprehensive yet still under extension, and control-walls against diversion. Parsenn Service cooperates in observation of the broader neighborhood and the carrying through of experiments in loosing avalanches artificially.

Past work and future tasks--The guiding idea and common goal of the previous joint effort of various specialists was the investigation of the physics of snow with special regard to the mechanics of avalanche-formation on the basis of a synthesis of theory, experiment, and observation of nature. The first results attained were published by the Commission in New Year 1939 in the comprehensive work "Der Schnee und seine Metamorphose," now being translated by the United States Forest Service and Weather Bureau.

To illustrate the practical working-out of the tasks so far completed, various faulty constructions of streets and roads have already been checked and redesigned along new standard lines submitted by the Weissfluhjoch Station. Likewise valuable advice was given for the protection of the military cable roads against creeping snow. The weekly bulletin distributed by radio and press regarding conditions of snow and avalanche in the Swiss Alps depends more and more on the reports at the Weissfluhjoch Station that has established a network of simple observation-stations spread over the entire Alpine Region. Furthermore, reference should be made to the Army Avalanche Service organized through the initiative of the Avalanche Commission and to the avalanche courses in which, through the personnel of the Commission in military activity, many officers and soldiers since the war were trained in modern snow- and avalanche-service. The neces-

sity of this instruction arises from the fact that in the last World War approximately 80,000 officers and soldiers met death because of avalanches.

In the winter of 1940-41 it was possible in two weekly courses to initiate about 50 higher forest-officials and workers in snow-observation, snow-mechanics, the computation of snow-pressure, and innovations in the field of avalanche-prevention. Recently the results of snow-investigation are also being handled in a lecture on snow-mechanics and avalanche-prevention in the Forestry Division of the Federal Technical Highschool. The battle against avalanches with special relationship to mountain troops and skiers has been aided among others by the booklet, "Lawinen, die Gefahr für den Skifahrer," published in late autumn 1940 jointly with the Parsenn Service.

Movie films of avalanches have been prepared both by the Swiss Avalanche Commission and Army, one emphasizing avalanche-physics and the other rescue. The two have been united by the United States Army in a sound film for instruction in mountain warfare [Trans. Amer. Geophys. Union, p. 389, 1940, p. 977, 1941, and p.442, 1942].

Indirect applications have already been made primarily through transfer of the newly developed methods to the field of underground investigation, sounding-technique, and glacier-research.

The new building--The main drawback to the previous method of procedure was that fellow-workers during their period of activity must spend the night at Davos. Furthermore, on Weissfluhjoch there was only one heated room in which often five to seven men were present at one time, thus disturbing individuals at their tasks. The laboratory was too small for the simultaneous work of crystalographers, engineers, and physicists and all investigations suffered under the disadvantage that the laboratory-temperature could not be regulated.

The site of the new building (see Figs. 10 and 11), after a thorough study of snow, foundation, view, and exposure, was chosen east of the railway-station and connected with it by a gallery. Its interior space is about 1,600 cubic meters and estimated cost approximately 250,000 francs, of which the Swiss Parliament has contributed 140,000 francs.

With respect to its highland population and mountain troops and as an international foreign center, Switzerland feels morally bound in the struggle against avalanches to do all that lies within the bounds of human power. To this struggle belongs, however, the full support of modern research, which will be fostered by the new institute. This is a genuine Swiss task, already begun through Dr. COAZ about 1870 and well recognized in its economic significance, which would find through the Institute its natural continuation and completion.

Under the general theme "The human side of snow," the Chairman has written in an article on snow-perils and avalanches [Sci. Mon., April, 1943] a word of recognition and caution regarding snow that has seemed innocent yet is most perilous.

Publicity

Publicity has now expanded to include forecasts and snow-survey data, maps of snow and water-supply, articles, films, and window-displays. Snow has finally become an essential interest.

Forecasts and data--Annual snow-survey data have become an established part of the United States Weather Bureau's climatological records and forecasts of stream-flow have long been published by State Cooperative Snow-Surveys and the Division of Irrigation of the United States Soil Conservation Service. Now the Division of Irrigation through JAMES C. MARR has published a summary of snow-survey data in the Columbia Basin, including all past measurements. This should induce other summaries from the many basins where snow-surveying has long been established. Such summaries are essential to the analyzing of accumulated problems in forecasting.

Snow-cover surveys by the Eastern Snow-Conference for the seasons of 1941-42 and 1942-43, have been compiled at the Weather Bureau Office, Hydro-Climatic Unit, Albany, New York. All cooperating agencies have been urged by the New York Cooperative Snow-Survey to make snow-surveys February 1, March 1, March 15, or such date as may seem desirable to indicate the maximum accumulation of snow on the ground at the end of winter. Supplemental surveys also are acceptable.

The Water Resources Review of United States and Canada is published by the United States Geological Survey in collaboration with the Dominion Water and Power Bureau. In addition to

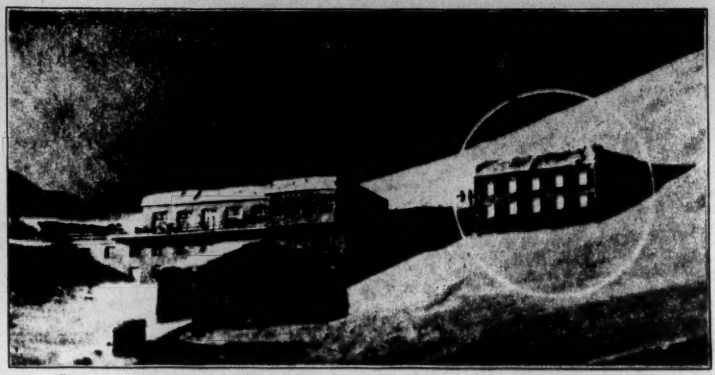


Fig. 10--Avalanche-Investigation Station Weissfluhjoch (in circle) from southeast (Photograph of model)

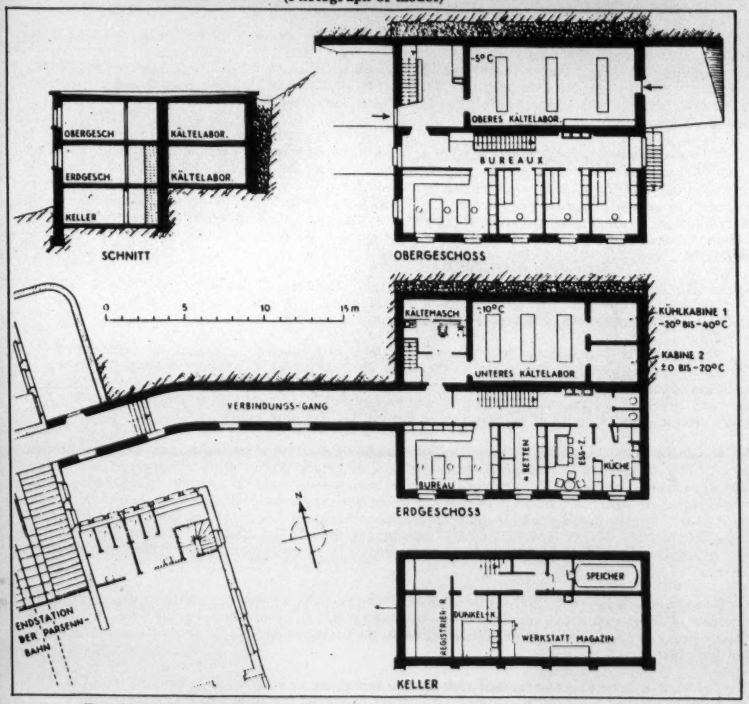


Fig. 11--Plans and section, projected new station on the Weissfluhjoch, Swiss Snow- and Avalanche-Investigation Commission

monthly reports of stream-stages is the seasonal report for October to March with an appendix containing the water-content of the snow and forecast of runoff.

Special news-bulletins with maps are also issued to the press by the Geological Survey, and appear under such headlines as, "Heavy storms in January help irrigation," "Favorable well supply assures industry, homes adequate water," "Water storage in West ten per cent less than year ago."

Lectures and articles--In addition to the original copies of the Proceedings of the Central Snow-Conference, Secretary Garstka reports that 3,700 copies of reprints were purchased by various contributors for distribution.

Although Mount Washington News-Bulletin No. 11 is the first since January 1942, seven of the 27 papers on the program of the Section of Meteorology at the annual meeting of the American Geophysical Union were based on Mount Washington data.

The original edition of 1,500 copies of Hydrology, the ninth volume in the series, Physics of the Earth, has been so nearly sold out that a second printing has been made. Reprints of individual chapters are not available.

Dr. CHARLES F. BROOKS lectured at Franklin Institute, Philadelphia, on snow-crystals and RICHARD C. FARROW spoke before the Royal Geographical Society in London on forecasting runoff from snow-surveys.

Among more formal articles are: "We are living in an ice age" by WELDON F. HEALD [Nat. History, December, 1941] based upon FRANÇOIS E. MATTHES' "Little ice age;" "Perennial snow and glaciers [Sci. Mon., March, 1943] and "Snow perils and avalanches" [Sci. Mon., April, 1943] by J. E. CHURCH; "Friction on ski" by GERALD SELIGMAN and "Friction on sledge runners" by FRANK DEBENHAM, being Parts I and II of "Friction on snow-surfaces" [The Polar Record, January, 1943].

Films--Instruction by film in the field of snow is being steadily extended. The United States Forest Service has translated the Swiss avalanche-film into English and has generously loaned it for showing. The United States Army has combined the two avalanche-films by the Swiss Avalanche Commission and Swiss Army into a sound film in English for the training of mountain troops. In exchange for the negative of the Swiss avalanche-film donated by the International Commission of Snow and Glaciers, the Army has supplied four positives. It is hoped that the Army may grant a copy of its joint-film for civilian use.

In addition to its "Manual of ski mountaineering," the Sierra Club after two winters' work by several photographers has produced a ski-mountaineering color-film entitled "Skis to the skyland" and shown it before mountain troops at Camp Hale, Colorado.

F. C. KOZIOL, Supervisor Teton National Forest, reiterates the value of the Tetons as a setting for an American avalanche-film as follows: "Of course war conditions would prohibit the initiation of any such project now, but eventually I would like to see an avalanche-picture made in this country. Such a film, made in color could be devised to serve as an educational medium for skiers who follow the sport in regions where avalanches are common."

Showings of the Swiss avalanche-film were made by the United States Forest Service, Sierra Club, Rocky Mountain Club, Colorado State College, Michigan State College, Maryland Academy of Science, the Washington (D.C.) Branch of American Meteorological Society, United States Soil Conservation Service, and Soda Springs Hotel (near Donner Summit of the Sierra Nevada). The sound-film "Formation of snow-crystals in the mountains and laboratory in Japan" was borrowed by the Sierra Club, Rocky Mountain Club, Franklin Institute of Philadelphia, and Haverford College. Both films have been loaned to Blue Hill Observatory for its collection of war-time instructional material.

Window-displays--The Current Information Section of the United States Soil Conservation Service has developed snow-survey window-displays featured by a shelter-cabin with its tall Santa Claus chimney accompanied by press-releases on the history and significance of snow-surveying (see Fig. 12).

Two such displays are presented with an accompanying news item at Boise, Idaho, as follows: "Snow-surveys play big part in agriculture (exhibit prepared for Boiseans depicts work of

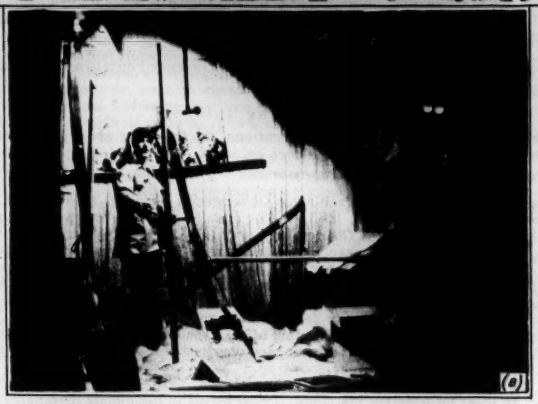


Fig. 12--Window-displays of snow-surveying

surveyors)--Wartime demands for record food-production and for hydroelectric power have centered attention this winter on the 'snow-crop' in the mountain watersheds from which western reservoirs are filled. Each winter, more than 2,000 men travel more than 75,000 miles on skis and snowshoes to measure the water-content of the mountain snowpack in Idaho and ten other western States.

"The hazardous work of the snow-surveyors, known professionally as 'niphometrologists' or 'niphometeorologists,' who are drawn from various private, State, and Federal groups, is under direction of the Soil Conservation Service of the United States Department of Agriculture.

"Southwestern Idaho snow-survey courses include those on the Boise, Payette, Weiser, and Owyhee river-drainages. Gem State surveys are handled by JAMES C. MARR of Boise, head of the Columbia Basin Surveys, who issues the up-to-the-minute reports to which irrigationists, power-officials, and others look for helpful water-forecast information necessary to planning their operations for dry summer months ahead.

"Snow-water data also are used in connection with numerous other activities, such as prospective flood-conditions, summer fire-hazards in the forests, crop-forecasting, estimating municipal water-supplies, and planning inland navigation-schedules.

"An unusually heavy snowpack over the Columbia Basin generally has been reported so far this season, which is interpreted by the snow-surveyors as presaging a favorable water-year in store for the area.

"A glimpse behind the scenes in this little-advertised profession of snow-surveying is given the residents of Boise and vicinity in a window exhibit now on at the C. C. Anderson store.

"Before about 1900, snow-testing was of depth only; but today, with special sampling-tubes and scales graduated to read in inches of water, the snow's water-content is determined. The snow-scientists explain that snow is nothing more than air and water, but that the proportions vary widely, and the difference of only a few inches of water in the mountain snow 'crop' means many dollars to the farmer in the irrigated valley and many tons of war crops for the armed forces, war workers, and lend-lease.

"This point was emphasized particularly by State Conservationist R. N. IRVING of the Boise Soil Conservation Service office, who arranged for the local exhibit. Conservation use of irrigation, livestock, farmstead, and other water, he pointed out, and of the land it supplies, especially for more food-for-freedom production, 'is of major importance in reaping a full harvest in the Boise valley and other areas from the snow-crop.'

"This agency is cooperating with farmers and ranchers in south western Idaho Soil Conservation districts and adjacent areas by giving technical and other available assistance with the application of conservation-farming practices that are vitally needed for present and continued high production of wartime food and fiber.

"On all but the most accessible snow-courses, the surveys are made by two men, as a precaution against storms, slides, and accidents. The measurements are taken on the major, representative drainages in established general storm-paths."

As postal advertisement, the envelopes containing snow-survey reports and forecasts of water-supplies bear the designation "SNOW-SURVEY REPORT."

Themes of leading interest

In place of the usual summary of leading publications, the following short papers and communications on themes of leading interest have been selected.

Icing-research

"Icing-research program of Mount Washington Observatory for 1942-1943" by DAVID L. ARENBERG [News Bulletin No. 11, April, 1943]--"The results of the research-program conducted on Mount Washington by members of the Observatory staff have been presented in recent publications and in a Master's thesis at the Massachusetts Institute of Technology on 'Meteorological factors affecting the icing of aircraft' (October 1942, microfilm copy available). The latter discusses at length the effectiveness of falling precipitation in diminishing the icing-hazard, variation of heavy riming with temperature and air-masses, measurement of liquid water in icing-clouds, and variation of deposits with size of collector and wind-velocity.

"While the progress made in the understanding of icing-phenomena has been substantial, it is felt that complete information has by no means been obtained and many new aspects of the main problem--when is it safe to fly--have been uncovered.

"Because of the prevailing high winds, low temperatures, and frequency of icing-fogs, Mount Washington makes an ideal location for the study. Observation in the clouds themselves can be made there of quantities impossible to duplicate in the laboratory and on a scale larger and safer than in a plane.

"It was proposed that the following program be undertaken by members of the Observatory staff with whatever aid may be necessary from other parties:

"(1) Preparation of routine reports of icing-conditions for relaying to the United States Weather Bureau with the regular three-hourly reports. A code for reports of liquid water, drop-size, density, and structural properties has been drawn up and is in use for aid to aviators flying in the vicinity of New England. If successful, it is hoped that other mountain stations, such as Mount Whiteface, may adopt this practice.

"(2) Measurement of liquid water-content will be continued as in the past. A new tower entered directly from the Observatory building offers facilities for more extensive measurements to be made and also more protection to the observers than in the past. The procedure of weighing the ice deposited on a small rotating cylinder during a given air-flow has proven very simple and accurate.

"(3) Measurement of collection efficiency by preliminary tests with cylinders up to 4.00 inches in diameter have shown that it is possible to derive empirically the amount of ice that will be deposited on a wing of given size. More extensive measurements on objects of different shapes would be of great help in solving a difficult mathematical problem. These measurements are compared with a standard air foil.

"(4) Measurement of drop-size distribution and variation with meteorological conditions. Some rapid method of determining drop-sizes is necessary and it has been shown that the procedure of comparing the collection-efficiency of two or more collectors provides this. An instrument of Professor H. G. HOUGHTON's, of the Massachusetts Institute of Technology, for photographing and measuring directly the sizes of the drops, was loaned to the Observatory and a direct check made of the accuracy of the first method. Continual use of the photographic method is not advisable because of the time required to reduce an observation. So far, more than 200 pictures have been made at temperatures extending to -40°F.

"(5) Determination of the presence of ice-crystals in water-clouds. To date no direct observations have ever been made of differences between the elements of ice- and water-clouds. As water-clouds will eventually turn into ice-clouds by the gradual freezing or sublimation of the super-cooled drops, it is important to know the factors controlling this transformation both because it represents a safe flying condition and because it controls the formation of rain. By making an extended series of microphotographs of fog-samples caught on a greased glass slide, the presence and number of ice-crystals can be readily found. If this is done in a suitable manner, the photographs may be of use also in determining the drop-size discussed in (4). The microscope is being supplemented by a monochromatic light beam from a mercury lamp. This will show halos in dense ice-crystal clouds and coronas in water-clouds. The coronas are readily seen.

"(6) Observations on the microscopic structure of rime were begun during the past year and will be continued. This is of interest because it shows the manner in which ice can gain a foothold on a smooth surface and the effect of impurities on the formation developed. [Results published in June, 1942, Bull. Amer. Met. Soc., reprints available.]

"(7) Chemical analysis of fog-water. The possibility that small amounts of impurities affect the surface-tension and therefore the ice-density has been pointed out. For this and other reasons it would be advisable to measure the organic as well as inorganic impurities in cloud-water. Measurements of conductivity, surface-tension, acidity, microörganisms, etc., could be combined. If facilities regarding time and equipment are not provided the observers, it might still be advisable to take a melted sample of rime daily in a sealed bottle for analysis at some convenient time and place.

"(8) Testing and development of instruments concerned with icing on aircraft. Because of the extreme weather conditions prevailing on Mount Washington, exposure-tests simulating actual flying-conditions are readily made. Long endurance-runs could be given there and the weak points of instruments determined more readily than on planes or in wind-tunnels. In spite of the importance of a knowledge of cloud-conditions for aviation, the principal factor limiting the scope of the research-program is the lack of manpower because of other war needs. The Observatory is at present understaffed and the men are well occupied with routine work. Unless at least one additional man is provided, preferably one with scientific training, who can devote full time to this project, the research-work will be under a severe handicap. It is felt, however, that no matter how little work is done anything accomplished will be a definite asset because this field is almost entirely new and unexplored."

Snow-surveys

"Forecasting runoff from snow-surveys" by Captain R. C. FARROW [Geogr. J., London, 17 pp., map, ills.]: A review by J. E. CHURCH. This paper, presented before the Royal Geographical Society, represents the carry-over into war's avocations of one's life enthusiasm and the fertile field offered by Great Britain for world science. Captain Farrow presents the transplanting of snow-surveying from the United States to Canada and discusses its adaptability to western Canadian climate and industry.

So completely are the reviewer and author in accord that the reader who cannot obtain access to the original article is referred to "Snow-surveying: Its principles and possibilities" [Geogr. Rev., October, 1933] solicited by Editor Wrigley, in her desire to aid in the development of frontier areas.

Snow-surveying is a hardy science and has received a hardy name, understandable to the man who knows snow and uses its product. Some enthusiastic engineers have proposed going formal with the technical name niphometrology (snow-measuring) but the plain names in hydrology, such as rain, snow, runoff, ground-water, have established a preventive precedent.

The Mount Rose Snow-Sampler that was basic to the development of the science is a special instrument adapted to the cutting and lifting of cores of snow. It penetrates yielding snow of any depth and reveals the structure and density of snow for water-studies or the detection of avalanche-tendency. In consolidated snow-crystals of considerable depth or thin ice-strata it can be forced but there is no means of lifting the ice-dust to the surface and the snow or ice that is melted by the friction quickly refreezes and imprisons the cutter. For ice-penetration some type of drill or auger must be employed, preferably with water to clear the accumulating ice-dust from the hole and prevent clogging.

Captain Farrow's activity in snow-surveying grew out of his membership in the Research Committee on the Hydrology of Snow of the American Geophysical Union. The custom of following

international streams across the border and seeking international cooperation, inaugurated by the Committee on Snow, has been followed by the Committee on Glaciers and more recently by the Committees on Precipitation and Ground-Water, for science knows no boundaries in its quest for human welfare. The author's love of winter landscape provides momentary relaxation in his narrative that concludes with the measuring of streams

Forecasting runoff in the Ebro Basin, Spain: A call for counsel

The power-installations on the Ebro, Spain, were constructed originally by JOHN C. STEVENS, Consulting Engineer and Regional Chairman of the Section of Hydrology at Portland, Oregon. After the lapse of years, the problem of forecasting water-supply for the project has been referred to the Nevada Agricultural Experiment Station in the following quoted letters from G. H. B. FISHER of the Canadian and General Finance Company, Limited, of Toronto, Canada, and E. H. CRETCHLEY for President and Managing Director F. FRASER LAWTON of Riegos y Fuerza del Ebro, S. A., of Barcelona, Spain. Here is an open door to international service that need not await the close of the war.

Letter of July 8, 1943, from Mr. Fisher to Chairman Church--"You will no doubt recall that under date of November 10th, 1942, you were good enough to send us a set of literature covering the methods and purposes of snow-surveying. Our request for this information was actually on behalf of our affiliated company in Spain, the Ebro Irrigation and Power Company, Limited, at Barcelona, some of whose hydro plants are in the foothills of the Pyrenees.

"In view of the difficulties in communicating with Spain, we decided to first send them a copy of your letter with a list of the literature sent under separate cover and inquire if they were sufficiently interested to have us forward all or part of it along. We have just this week received their reply of February 3, a copy of which we are attaching for your information and from which you will note that they are much interested in this subject. We shall now send along the reprints which they have requested and if, after reading the enclosed letter, there is any other published data that you think might be useful to them, we would appreciate your advising us."

Letter of February 3, 1943, from Mr. Cretchley to the Canadian and General Finance Company, Limited--"I have to thank you for your letter of November 25 and for kindly sending copy of the notes re the matter of measurement of snow, that you received from the University of Nevada. Your letter has been forwarded to our Technical Manager, Mr. POMEROL, who would be very glad to receive a copy of the articles that appear in the list attached to your letter.

"We are very interested in the matter of snow-conditions in respect of their relation to our hydraulic storage-situation and have kept records for many years of the depth of snow each season in certain places. We have found, however, that these records are of little practical use, and are of the opinion that the only data on which any reliance can be placed are those furnished by a totalizing pluviometer in which both snow and rain are collected in a receptacle in which is initially placed a certain quantity of concentrated solution of calcium chloride on the top of which is an oil-film to avoid evaporation. The type of pluviometer which we use is that known as the 'Mougin' with an orifice of 200 mm^2, protected against the effect of wind by an inverted truncated conical sheet-zinc protection.

"We should, however, be most interested to know the experience of others in gaging the amount of hydraulic storage from records of snow-surveying. The principal difficulties that we have found have been: (1) The effect of wind and steep slopes, which produces enormous variations in the depths of the snow-deposits; (2) the absence of large relatively level areas in the mountainous district in which we are interested; (3) the large variations in snow-density resulting from the conditions under which it has been deposited. If there have been alternate cold and snowy periods followed by sunshine or light rain, the snow is of much greater density than if the temperature has remained below zero during the whole period of deposition.

"Conditions here in Spain are, no doubt, different to those in America. In the eastern Pyrenees the lower limit of permanent snow, during the winter months, lies between 1,600 and 2,000 meters, but the amount of snow deposited and the intervals of fine and bad weather in the months from December to March are very variable in their distribution over this period from one year to another.

"Experience has shown that there is a cyclic variation of total annual precipitation which produces a dry year on the average every five or six, the remainder varying between wet and medium years.

"Our main hydraulic storage can be considered as divided into two parts, corresponding roughly to the original 'Energia' and 'Riegos' developments respectively. The 'Energia' development consists of a series of lakes situated in a small watershed of about 29 km^2 at an altitude above 2,000 meters, while the 'Riegos' system is based on the Tremp Reservoir, situated at an

altitude of 500 meters and fed from a watershed of about 2,000 km^2, 50 per cent of which is over 1,600 meters high.

"The maximum storage-capacity of the 'Energia' system is slightly under 50 million cubic meters and each cubic meter can produce about 3.4-KW hours in its passage through the various power-stations in series on our system. The capacity of the Tremp Reservoir is 200 million cubic meters (162,000 acre-feet), each cubic meter producing about 0.55-KW hour.

"Our normal annual hydraulic storage-cycle usually commences in June with full storage resulting from melting snow, and in favorable years we are able to commence the winter period in October also with full reservoir, this being steadily drawn down at a rate depending on the amount of rain falling to a minimum in April at the commencement of the period of melting snow.

"The Camarasa Reservoir, of 100 million cubic meters, downstream from Tremp, is also an important secondary factor, but is operated as a regulating as well as a storage-reservoir.

"In 30 years' experience we have found that the snow available in the large area supplying Tremp Reservoir, has been sufficient to fill it every year, and we have therefore not found it justified up to the present to investigate snow-storage in the watershed, a matter which, in any case, would be difficult and expensive to do properly, owing to the extent and very mountainous nature of the majority of the area concerned.

"In 1929, however, the Tremp Reservoir was only just filled and this circumstance may again arise in the future with the increase of system load, should the supply from other stations, independent of the Tremp Reservoir, not come up to expectations. Under these circumstances in certain years we would be very interested in being able to gage the probable total flow from the melted snow in the Tremp Reservoir Watershed.

"The small area supplying the 'Energia' lakes above Capdella, however, is one in which we are always interested in being able to gage the amount of water we can expect to get each year. The storage in the lakes is considered as divided into two parts: 'A' and 'B'. 'A'-storage is that part of the total amount which experience has shown us we can rely on replacing even in the most unfavorable years. 'B'-storage is the remainder which we cannot rely on replacing each spring. If, however, a reliable snow-survey could be made we would better be able to judge the proportion of the storage which we would be likely to be able to replace in the spring in any particular year. The area though small is, however, very mountainous with steep inaccessible slopes rising to a height of nearly 3,000 meters in places. For this reason we have come to the conclusion that the easiest and most reliable method of gaging the snow-storage is, as before mentioned, the totalizing pluviometer which we have installed at a position in the area where there is a permanent staff all the winter.

"One very important factor in this matter is the question of evaporation. We have found in several years that an apparently large deposit of snow did not produce the amount of river-flow that we expected, and presumably the reason for this was that a large proportion had been evaporated during May and June from the surface of the snow under the action of the Sun. The ideal conditions for obtaining the maximum river-flow from a given snow-deposit are obviously warm rainy weather.

"We think the foregoing may be of interest to the University of Nevada which has kindly provided you with the information that you sent us and for our part we should be interested in having any comments or suggestions that they may care to make as a result of their experience and which would be helpful to us."

Recent Soviet publications on snow and ice

The value but inaccessibility of accumulating Soviet literature on snow and ice and the need of translations is stressed in the following note from the Polar Record [p. 577, July, 1942]:

"In the Report of the Committee on Snow, 1939-40 [Trans. Amer. Geophys. Union, pp. 750-779, 1940], Professor B. P. WEINBERG, of the Central Physical Laboratory, Leningrad, gives a valuable list of recent Soviet publications on snow and ice. The titles of 694 papers are arranged alphabetically under the names of the authors, and are classified under the following headings: (A) General (except on frozen ground, under-water ice and glaciers); (B) underwater (anchor-) ice studies; (C) studies on permanently frozen ground and on freezing soil. Rather unexpectedly, there are no papers on glaciers.

"The authors, titles, and sources are given only in English form, but the bibliography concludes with a list of transliterated names of the 78 Soviet periodicals to which reference is made, and a note on the system adopted. This procedure has been followed owing to uncertainty regarding methods of transliteration to be used in the proposed International Bibliography of Snow and Ice.

"The titles indicate the main trends of Soviet research and the enormous amount of work on these subjects during the last decade. The concentration on investigations having an immediate practical application in every-day human affairs is particularly noteworthy. The main lines of research have been concerned with (1) Problems of construction of foundations for houses, roads,

bridges, dams, water-supply pipes, etc., in permanently frozen ground; (2) agricultural experiments in the regions of prolonged frost: (3) studies of the formation and movements of sea-ice, especially in shipping routes; (4) the development of mechanical transport and sledges, and the relation of their bearing surfaces to the physical properties of snow and ice; (5) the control of snow-drift; (6) the icing of airplanes; (7) the forecasting of weather conditions, especially in relation to snow-cover and runoff of melt-water; (8) the problems of cold storage of food.

"It is most unfortunate that this work is largely ignored outside the USSR. Nearly all the reports are published in Russian, and only a small number appear to be accompanied by brief summaries in English, German, or French. In addition to the difficulties of translation, remarkably few of the publications are available in libraries outside the USSR. To anyone who has attempted to investigate this literature, which is appearing in annually increasing volume, it is clear that little progress will be made in other countries unless translations and summaries are made available, and contact and discussion are developed."--B. B. R.

Tribute

Tribute must be paid to J. D. McVICAR, Maintenance Engineer who has now retired from the Highway Department of the State of Washington, for his pioneer work in the physics of snow-removal. He fulfilled the faith of the Chairman that snow-removal was more than mechanics.

Losses by death and entry into war service have been serious. Most of the latter will return to their earlier tasks. A roster of snow-men in service has been suggested. Their value to winning the war is high.

The International Commission of Snow and Glaciers has lost Dr. DAN la COUR of Denmark, chosen President of the International Union of Geodesy and Geophysics because of his initiative in developing the Second International Polar Year, 1932-33, and Dr. MAX DEMOREST, specialist in glacier-flow--both indispensable.

And snow-surveying has lost an artist-craftsman in the recent death of ROY F. CURTIS, photographic counselor and associate of the Chairman in his snow-studies on Mount Rose.

Appreciation

In addition to the usual word of appreciation to the Nevada Agricultural Experiment Station that has been the physical and spiritual patron of the Committee on Snow, special mention should be made of the assistance of Lieutenant-Colonel BESTOR ROBINSON and Captain RICHARD M. LEONARD of the Quartermaster General's Office in obtaining close cooperation with the Army Air Forces in charge of the weather service. Colonel Robinson writes, "If this helps your program I can feel that my membership on the American Committee on Snow has been of some help after all."

APPENDIX A--ADDRESSES OF PERSONNEL OF COMMITTEE ON SNOW

Officers

Dr. J. E. Church (Chairman), Meteorologist, Nevada Agricultural Experiment Station, University of Nevada, Reno, Nevada

W. U. Garstka (Vice Chairman), Project Supervisor, U. S. Soil Conservation Service, Michigan Agricultural Experiment Station, East Lansing, Michigan

Captain R. C. Farrow, 1 Calibration Troop, R.C.A. Overseas (Hydraulic Engineer, Water Rights Branch, Department of Lands, Victoria, British Columbia, Canada)

Lt.-Col. Carl H. Elges (Assistant Meteorologist, University of Nevada, Agricultural Experiment Station, Reno, Nevada)

Water-supplies

W. W. McLaughlin, Chief Division of Irrigation, Soil Conservation Service, Box 180, Berkeley, California

L. K. Sherman, Consulting Engineer, 53 West Jackson Boulevard, Chicago, Illinois

R. K. Barrows, Prof. Emeritus of Hydraulic Engineering, Massachusetts Institute of Technology, Boston, Massachusetts

Evaporation

Joseph Kittredge Jr., Professor of Forestry, University of California, Berkeley, California

François E. Matthes, Senior Geologist, U. S. Geological Survey, Washington, D. C.

Floods

Merrill Bernard, Hydrologic Director, U. S. Weather Bureau, Washington, D. C.
G. A. Hathaway, Head Engineer, Office of the Chief of Engineers, War Department, Washington, D. C.
Gerard H. Matthes, Member, Mississippi River Commission, Vicksburg, Mississippi

Snow-cover and physics of snow and ice

Lt.-Col. Bestor Robinson, Q.M.C. Assistant, Office of the Quartermaster General, War Department, Washington, D. C.
Dr. Henry I. Baldwin, Assistant Forester, Forest Research, State of New Hampshire, Hillsboro, New Hampshire
Salvatore Pagliuca, Chief Meteorologist, The Yankee Network, 21 Brookline Avenue, Boston, Massachusetts
Dr. Howard T. Barnes, Professor Emeritus of Physics, Queen City Park, Via Burlington, Vt.
Dr. Phil E. Church, Research Associate, Institute of Meteorology, University of Chicago, Chicago, Illinois
Robert G. Stone, Research Associate, Department of Meteorology, New York University, University Heights, New York
Dr. Ralph L. Belknap, University of Michigan, Ann Arbor, Michigan
Walter T. Wilson, U. S. Weather Bureau, Washington, D. C.
Ray K. Linsley, Jr., Associate Hydrologic Engineer, U. S. Weather Bureau, Sacramento, California

Transport

J. D. MacVicar, c/o Department of Highways, Olympia, Washington
Lacey V. Murrow, c/o Department of Highways, Olympia, Washington

Regional representatives

Paul L. Bean, Agent and Engineer, Union Water Power Company, Lewiston, Maine
E. S. Cullings, Secretary, Black River Regulating District, Watertown, New York
Lt.-Col. D. B. Freeman, Corps of Engineers, Missouri River Division, 206 South 19th Street, Omaha, Nebraska
James C. Marr, Irrigation Engineer, Box 835, U. S. Soil Conservation Service, Boise, Idaho
E. B. Debler, Hydraulic Engineer, U. S. Reclamation Service, Denver, Colorado
Harlowe M. Stafford, District Engineer, U. S. Geological Survey, Los Angeles, California
Dean George D. Clyde, College of Engineering, Utah State Agricultural College, Logan, Utah
H. P. Boardman, Professor Emeritus of Civil Engineering, University of Nevada, Reno, Nevada
Fred H. Paget, Associate Hydraulic Engineer, Department of Public Works, Division of Water Resources, Sacramento, California
J. H. Ryan, Assistant State Engineer, in charge Oregon State Snow Surveys, Salem, Oregon
E. H. Collins, Assistant Chief Engineer, Washington Water Power Company, Spokane, Washington
R. A. Work, Associate Irrigation Engineer, U. S. Soil Conservation Service, Medford, Oregon
Eric Hinton, Engineer, International Power and Paper Company of Newfoundland, Deer Lake, Newfoundland
Matthew Balls, The Shawinigan Water and Power Company, Montreal, Canada
O. H. Hoover, Engineer-in-Charge, Dominion Water and Power Bureau, Calgary, Alberta, Canada
William H. Hobbs, Professor Emeritus of Geology, University of Michigan, Ann Arbor, Michigan
Laurence M. Gould, Professor of Geology and Geography, Carleton College, Northfield, Minnesota

Nevada Agricultural Experiment Station,
Reno, Nevada, July 20, 1943

APPENDIX B--LIST OF CURRENT PUBLICATIONS ON SNOW AND ICE

H. P. Boardman and Ralph W. Burhoe

SNOW

(1) General

Anti-frostbite ointments, The Polar Record, v. 4, No. 25, p. 30, 1943.

CENTRAL SNOW-CONFERENCE, Proceedings East Lansing, Michigan, 1942.

J. E. CHURCH, Annual report of Committee on Snow 1941-42, Trans. Amer. Geophys. Union, pp. 393-449, 1942; Appendix A, RALPH W. BURHOE and H. P. BOARDMAN, List of current publications on snow and ice [pp. 450-461].

Ice accumulation near airplane-wing slots prevented, The Frontier (Armour Res. Foundation, Chicago), v. 6, No. 2, p. 12, June, 1943.

Red and violet snow, Science, v. 96, No. 2495, p. 10, October 23, 1942.

(2) Precipitation and evaporation

W. R. BALDWIN-WISEMAN, Drought studies, Eng. News-Rec., v. 130, p. 279, February 25, 1943.

MERRILL BERNARD, Report of Committee on Rainfall, 1941-42, Trans. Amer. Geophys. Union, pp. 462-464, 1942.

HARRY F. BLANEY and KARL V. MORIN, Evaporation and consumptive use of water, empirical formulas, Trans. Amer. Geophys. Union, pp. 76-83, 1942.

J. H. DYSON, The snowfall in East Kent in recent years, Quart. J. R. Met. Soc., v. 68, pp. 261-262, 1942.

KATHERINE CLARKE-HAFSTAD, The spacing of rain-gages and the measurement of flood-producing rain, Trans. Amer. Geophys. Union, pp. 557-558, 1942.

W. M. JOHNSON, The interception of rain and snow by a forest of young ponderosa-pine, Trans. Amer. Geophys. Union, pp. 566-570, 1942.

LUNA B. LEUPOLD, Characteristics of heavy rainfall in New Mexico and Arizona, Proc. Amer. Soc. Civ. Eng., v. 69, No. 2, February, 1943.

Maximum possible precipitation over the Ohio River Basin above Pittsburgh, U. S. Waterways Exp. Sta. Vicksburg, Mississippi, Hydromet. Rep. No. 2, 1941.

C. H. NIEDERHOFF and H. G. WILM, Effect of cutting mature lodgepole-pine stands on rainfall-interception, J. Forestry, v. 41, p. 57, 1943.

Record 24-hour rainfall in Southern California, Eng. News-Rec., v. 130, p. 263, February 18, 1943.

(3) Snow-surveying

Columbia Basin, Summary of snow-survey data in Columbia Basin including all past measurements, Div. Irrig., Soil Cons. Ser., November, 1942.

Federal snow-surveyor, under Meteorology in Encyclopaedia Britannica Book of the Year 1943.

FRANK B. HARPER and JACK G. JAMES, Snow water, Soil Cons., v. 7, pp. 3-9, 1941.

C. H. NIEDERHOF and E. G. DUNFORD, Some possible errors in snow-sampling, Rocky Mountain Forest Experiment Station, Fort Collins, Colorado, 1942, 5 pp. MS; also Trans. Amer. Geophys. Union, p. 557, 1942.

Snow cover surveys, Eastern Snow Conference, Seasons of 1941-42 and 1942-43, U. S. Weath. Bur.

Water content of snow, spring 1943, Water Res. Rev., U. S. Geol. Surv. in collaboration with Canada, Dominion Water Power Bur., pp. 12, Appendix, October 1, 1942, March 31, 1943.

(4) Forecasting

H. P. BOARDMAN, Forecasts versus runoff for Central Sierra, Eastern Slope, Trans. Amer. Geophys. Union, pp. 155-156, 1942.

J. E. CHURCH, Forecasts versus runoff for the Humboldt Basin, Nevada: Two unusual years, 1940-41 and 1941-42, Trans. Amer. Geophys. Union, pp. 156-159, 1942.

R. C. FARROW, Forecasting runoff from snow surveys, Geog. J., v. 100, p. 206, 1942.

S. H. FRAME, Forecasts versus runoff for Columbia, Kootenay, and Okanagan basins and the coastal belt adjacent to Vancouver, Trans. Amer. Geophys. Union, pp. 159-161, 1942.

L. STANDISH HALL, Forecasting versus runoff for Mokelumne Watershed, Trans. Amer. Geophys. Union, pp. 153-155, 1942.

WILLIAM A. LANG, Forecasts versus runoff tributary to storage-reservoirs on Upper San Joaquin River, Trans. Amer. Geophys. Union, p. 155, 1942.

Nevada Forecasts, Eng. News-Rec., v. 129, No. 1, p. 24, July 2, 1942.

FRED H. PAGET, Forecasts versus runoff for California for 1941, Trans. Amer. Geophys. Union, p. 153, 1942.

SNOW--Continued

(6) Runoff-factors: Hydrology

L. R. BEARD, Statistical analysis in hydrology, Proc. Amer. Soc. Civ. Eng., v. 68, p. 1077, 1942.

M. H. COLLET, Crest stage meter for measuring static heads, Civ. Eng., v. 12, p. 396, July, 1942.

MAURICE DONNELLY, Water-storage by California hill soils in the season of excessive rainfall, 1940-41, Trans. Amer. Geophys. Union, pp. 544-553, 1942.

FLOYD J. DORAN, High water gaging, Civ. Eng., v. 12, p. 103, February, 1942.

G. E. FERGUSON, Crest stage gage, Civ. Eng., v. 12, p. 570, October, 1942.

L. T. GUY, Unique method of gaging high water, Civ. Eng., v. 12, p. 397, July, 1942.

W. W. HORNER and S. W. JENS, Surface runoff determination from rainfall without the aid of coefficients, Trans. Amer. Soc. Civ. Eng., v. 107, p. 1039, 1942.

JOHN C. HOYT, Development of the science of river measurement hydrology, Civ. Eng., v. 12, p. 324, June, 1942.

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MAURICE PARDÉ, Role de la Neige dans les Crues, Rev. l'Etude des Calamites, v. 5, pp. 26-36, 1942.

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MERRILL BERNARD, Primary role of meteorology in flood flow estimating, Proc. Amer. Soc. Civ. Eng., v. 69, p. 105, January, 1943.

C. G. COMMONS, Flood hydrographs, Civ. Eng., v. 12, p. 571, October, 1942.

Floods caused by heavy December rains, Eng. News-Rec., v. 130, p. 3, January 7, 1943.

Flood due to break of an earthfill dam in Idaho, Eng. News-Rec., v. 131, p. 109, July 8, 1943.

W. E. HOWLAND, Methods of estimating flood frequencies, Civ. Eng., v. 13, p. 185, April, 1943.

Heavy rains in May cause record breaking floods along the Arkansas River and elsewhere, Eng. News-Rec., v. 130, p. 720, May 20, 1943; also v. 130, pp. 767-770, May 27, 1943, and v. 130, p. 782, June 3, 1943.

W. W. HORNER, The role of the land during flood periods, Proc. Amer. Soc. Civ. Eng., v. 69, p. 665, May, 1943.

Missouri River flood in April caused by heavy rains and melting snows, Eng. News-Rec., v. 130, p. 535, April 22, 1943.

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RALPH W. POWELL, A simple method of estimating flood frequency, Civ. Eng., v. 13, p. 105, February, 1943.

RALPH W. POWELL, Comments on estimating flood frequencies, Civ. Eng., v. 13, p. 231, May, 1943.

REGINALD C. PRICE, The Gumbel method of estimating flood frequencies, Civ. Eng., v. 13, p. 285, June, 1943.

HARRY WIERSEMA, Floods on the Tennessee: Beneficial results by reservoir operation, Eng. News-Rec., v. 130, p. 413, March 25, 1943.

(8) Conservation

W. M. JOHNSON, The interception of rain and snow by a forest of young ponderosa-pine, Trans. Amer. Geophys. Union, pp. 566-570, 1942.

Snow (Note on function in supplying water for agriculture), Science, v. 97, Supp. p. 10, February 5, 1943.

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(9) Snow-removal

Added lights on Ohio snow-plows reduce accidents, Eng. News-Rec., v. 129, p. 183, July 30, 1942.

R. H. BALDOCK, Removing snow from airports, Eng. News-Rec., v. 129, p. 835, December 17, 1942.

C. G. BATES and J. H. STOECKELER, Planting to control snow drifts on highways, Eng. News-Rec., v. 129, p. 92, July 16, 1942.

SNOW--Concluded

(9) Snow-removal--Concluded

Canadian cities short of labor for snow removal, Eng. News-Rec., v. 129, p. 529, October 15, 1942.

HAL W. HUNT, Fighting snow to keep 'em flying, Eng. News-Rec., v. 129, pp. 641-652, November 5, 1942.

Road Equipment to be pooled under State wide plan, Eng. News-Rec., v. 130, p. 321, March 4, 1943.

Several Canadian cities dubious about availability of man-power for snow removal during coming months, Eng. News-Rec., v. 129, p. 529, October 15, 1942.

M. W. TORKELSON, Planted snow fences, Eng. News-Rec., v. 129, p. 408, September 24, 1942.

(10) Transport, winter-sports, avalanches

Arctic manual (U. S. War Dep.), Washington, 1942, 74 pp. (Ch. 2, pp. 11-25, on climate and weather).

J. E. CHURCH and A. L. SONDEREGGER, Motion film of Swiss avalanches, Trans. Amer. Geophys. Union, pp. 151-152, 1942.

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P. H. DUCKER, Winter transportation in the High Sierras by Sno-Motor, Trans. Amer. Geophys. Union, pp. 161-163, 1942.

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G. SELIGMAN and FRANK DEBENHAM, Friction on snow surfaces, ski and sledge runners, Polar Record, v. 4, pp. 2-11, January, 1943.

Shortage of funds and equipment to prevent snow removal from Oregon's scenic highways, Eng. News-Rec., v. 129, p. 692, November 19, 1942.

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ICE

(1) General

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NEVIN M. FENNEMAN, Memorial to Max Harrison Demorest, Proc. Geol. Soc. Amer., Annual report for 1942, pp. 173-177, April, 1943.

HOYT LEMONS, Hail as a factor in the regional climatology of the United States, Geog. Rev., v. 32, pp. 471-475, 1942.

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(2) Sea and river ice

RICHARD FINNIE, Canada moves north, Ice flows Baffin Bay, Ref. (?), New York, 1942.

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B. SWENSON, Ice in rivers of the United States: Opening and closing dates of river navigation in the United States, Mon. Wea. Rev., v. 70, 1942.

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(3) Glaciers

A. T. BOWDEN, Nabesna Glacier and Mt. Blackburn, Wrangell Range, Alaska, Man's Physical Universe, New York, 1943, 145 pp.

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JOHN L. RICH, Buried stagnant ice as a normal product of a progressively retreating glacier in a hill region, Amer. J. Sci., v. 241, pp. 95-100, 1943.

G. SELIGMAN, Glacier fluctuation, Quart. J. R. Met. Soc., v. 69, p. 66, 1943.

(4) Underground ice; frost in soils

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JOHN L. RICH, Buried stagnant ice as a normal product of a progressively retreating glacier in a hilly region, Amer. J. Sci., v. 241, pp. 95-100, 1943.

(5) Polar

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REPORT OF COMMITTEE ON GLACIERS, 1942-43

François E. Matthes, Chairman
(Published with the approval of the Director of the Geological Survey)

The personnel of the Committee at present is as follows:

Harry Fielding Reid, Professor Emeritus of Geology, Johns Hopkins University, 608 Cathedral Street, Baltimore, Maryland
William H. Hobbs, Professor Emeritus of Geology, University of Michigan, Ann Arbor, Michigan
Colonel Lawrence Martin, Chief, Division of Maps, Library of Congress, Washington, D. C.
James E. Church, Professor of Meteorology and President, International Commission of Snow and Glaciers, Agricultural Experiment Station, University of Nevada, Reno, Nevada
First Lieutenant William Osgood Field, Jr., home address, 18 West Twelfth Street, New York City
Oliver Kehrlein, Chairman, Committee on Glacier Studies, Sierra Club, 1050 Mills Tower, San Francisco, California
Kenneth N. Phillips, Associate Hydraulic Engineer, Water Resources Branch, Geological Survey, Chairman, Research Committee of the Mazamas, 606 Post-Office Building, Portland, Oregon
William S. Cooper, Professor of Botany, University of Minnesota, Minneapolis, Minnesota
Lieutenant Colonel Gerald FitzGerald, Army Air Corps, Washington, D. C.
Laurence M. Gould, Professor of Geology, Carleton College, Northfield, Minnesota
Arthur Johnson, Hydraulic Engineer, Conservation Branch, Geological Survey, 1105 Washington Building, Tacoma, Washington
François E. Matthes (Chairman), Senior Geologist, Section of Glacial Geology, Geological Survey, Washington, D. C.

The Committee is fortunate in having its membership reinforced by the addition of ARTHUR JOHNSON, who for several years has had charge of the repetitive plane-table surveys of the lower Nisqually Glacier, on Mount Rainier--a project which the Geological Survey is carrying on in cooperation with the city of Tacoma, Washington. To him the Committee is indebted for data concerning the losses in volume of ice which the Nisqually Glacier is sustaining from year to year.

On the other hand, through the death of MAX HARRISON DEMOREST, on November 30, 1942, the Committee has lost an esteemed and active member, who was engaged in a unique type of glaciologic research that had not been essayed previously on this side of the Atlantic--a crystallographic study of the changes that take place in the crystal-fabric of the ice under the differential stresses to which it is subjected in a moving glacier. Demorest gave up that important research in 1942 in order to serve his country with the armed forces--gave it up before he had been able to carry it to completion and publish the results in full. Aside from the keen personal loss which his fellow members on the Committee feel at the departure of one for whom they had a warm affection as well as genuine admiration, they realize that his genius cannot be replaced, and that the gap which his death leaves in their ranks is likely to remain unfilled for some time to come.

Demorest lost his life in Greenland, where, commissioned as First Lieutenant in the Army Air Corps, he was giving that arm of the service the benefit of his intimate knowledge of the glacial and climatic conditions peculiar to that arctic country. Of the tragic accident in which he met death a brief account is given in a note appended to his memorial elsewhere in these Transactions [see pp. 12-16].

A most fortunate circumstance it is, in any event, that Demorest did set forth very fully his conception of the fundamental laws of glacier-motion. Convinced by his earlier observations on the Greenland Ice-Sheet and on mountain glaciers in the United States, as well as by his laboratory experiments, that glacier-ice in large masses yields to slowly applied forces by differential deformation, like a plastic substance, he showed that glacier-motion is primarily of the nature of gravitational flowage, and at the same time he recognized, what no one before had clearly apprehended, that obstruction of such flowage must give rise to localized shearing movements. He thus demonstrated how those two antithetic types of movement are related to each other and can occur simultaneously in one and the same ice-mass; and he thereby provided the key to the solution of a problem that has been the subject of vexing controversies ever since the dawn of glacial science.

The two papers in which Demorest gave this epoch-making exposition are: (1) "Glacier regimens and ice-movement within glaciers," forming part I of the study of "Glacier-thinning during deglaciation," which he and RICHARD FOSTER FLINT published conjointly [Amer. J. Sci., v. 240, pp. 29-66, 1942]; and (2) "Ice-sheets" [Bull. Geol. Soc. Amer., v. 54, pp. 363-400, 1943].

It may appropriately be added that before the first of these two papers was published, the present writer was accorded the privilege of reading it in manuscript and of discussing its contents with the author. Satisfied of the essential soundness of the reasoning, and impressed with the fundamental importance of the laws of glacier-mechanics laid down in it, the writer obtained Demorest's consent to the incorporation of those laws in the chapter on "Glaciers," which then was being prepared for the volume on Hydrology, No. 9 of the Physics-of-the-Earth Series. Indeed, those parts of the chapter that deal with the subject of motion in ice-streams and ice-caps were largely built around Demorest's laws. And so it was that their acceptance was announced in the Hydrology volume, in 1942, almost simultaneously with the appearance of Demorest's first paper.

Although the personnel of the Committee otherwise remains unchanged, some of its members have been called away from their normal occupations by war duties and consequently are unable for the time being to contribute much to the Committee's work. Dr. GOULD is now Chief of the Arctic Section of the Arctic, Desert and Tropic Information Center of the Army Air Corps, with headquarters at the University of Minnesota. "It is the function of this organization," he writes, "to collect and disseminate information concerning the arctic regions for the use of the Army Air Forces. The organization will consist of 12 to 15 officers who are specialists in various phases of arctic conditions or operations. We shall have wide opportunity for field-research in the carrying out of the various projects which we shall have to do. Professor FLINT of Yale has just been commissioned to serve with us. I had also looked forward to requesting the transfer of MAX DEMOREST to this unit upon his return from the assignment on which he lost his life so tragically. I have known Max for many years and have had an increasingly high regard for him as a person and as a growing scholar in the field of glaciation."

WILLIAM OSGOOD FIELD, Jr., who in recent years has been the principal student of Alaskan glaciers, was commissioned a First Lieutenant in the Signal Corps of the Army. He was first stationed at Yellow Springs, Ohio, but according to a letter he wrote from Edmonton, Canada, December 27, 1942, he had been transferred to the Cold Weather Detachment. His repeated sojourns in Alaska should fit him well for the experimental work which that detachment is called upon to perform.

GERALD FITZGERALD is Lieutenant Colonel in charge of the Aeronautical Chart Service, at Headquarters of the Army Air Forces, Washington, D. C. His prolonged training and experience in topographic mapping, and especially in the utilization of aerial photography in map-making, in the Alaskan Branch of the Geological Survey, naturally make him an extremely valuable man for his new post.

Although the contingencies arising in connection with the present war effort thus operate to deprive the Committee of the active cooperation of several of its members, nevertheless, its work is by no means stopped, as will be evident from the data reported in the following pages. For that matter, there is no little satisfaction in the thought that in this crucial epoch the technical knowledge and the field-experience of even such highly specialized scientists as glaciologists are of real and very practical value to the armed forces of our country.

Glaciers of Glacier National Park, Montana

Superintendent D. S. LIBBEY reports that in the fall of 1942, for the first time in several years, most of the ice-bodies in Glacier National Park held their own, or at most melted back but slightly. The period of rapid recession which during past years has threatened these glaciers with early extinction appears to have come to an end, or, at least, to have been interrupted. This change for the better Mr. Libbey attributes not to unusually heavy snow-precipitation during the winter of 1941-42, but rather to the low temperatures and recurrent snow-storms that prevailed during the spring and early part of the summer. The total snowfall for the year was a little above normal, but the warm weather came late. As a result snow remained lying at the higher altitudes far into August, and some of the glaciers were still largely blanketed with snow in September.

Blackfoot Glacier, when visited by Park Naturalist M. V. WALKER on September 5, 1942, was still snow-covered all the way down to its terminus. With reference to the red lines that had been painted on the rock-floor along the ice-margins in 1941, the main ice-tongue had advanced 12 to 15 feet, but its sides had melted back four to six feet. The losses therefore practically counterbalanced the gains, and the glacier as a whole was regarded as essentially unchanged.

Grinnell Glacier, Mr. Walker reports, also had advanced slightly at some points along its margins, covering up the red lines painted the year before, but it had remained stationary at other points. It therefore is reported unchanged.

Sperry Glacier on September 4, 1942, was found divested of its snow-mantle along parts of its frontal margin, and especially on its main lobe, which projects from the northeastern end of the mass. As a consequence that lobe had melted back 21 feet from the marker set in 1941. Other parts of the broad front had receded somewhat less.

Agassiz Glacier, in contrast to the preceding, appeared to be still receding and disintegrating at a rapid rate. On September 9, 1942, its main ice-tongue had retreated not less than 2,276 feet from the markers set in 1938. This would imply an average recession of 569 feet per year. However, there is good reason to believe that recession was not uniform throughout the period, but most active during the first half. Although no measurements were made between 1938 and 1942, it is evident from JAMES L. DYSON's observations and photographs that already in 1940 the Agassiz Glacier had suffered a "phenomenal reduction" in extent and thickness, and that its general condition approached closely the present one [James L. Dyson, Recent glacier recession in Glacier National Park, Montana, J. Geol., v. 49, No. 8, pp. 815-824, 1941]. As Dyson has pointed out, moreover, reduction was effected not merely by progressive shortening of the ice-tongue, but also by its severance from the upper part of the glacier. "In the fall of 1937," he writes, "Agassiz Glacier was found to be almost severed into two parts, and between then and September 9, 1940, ... the separation had become complete."

The appearance of the glacier in that strangely divided state is shown clearly in Figure 5 of Dyson's paper [p. 821]; in contrast, the full-bodied aspect of the glacier in 1913 is shown in a photograph by Dr. WILLIAM C. ALDEN, of the Geological Survey, in Figure 6 [p. 822]. It was then a magnificent, continuous ice-mass, one of the largest in the Park, and well worthy of the name of LOUIS AGASSIZ.

At the beginning of this century, when the Kintla Lake Quadrangle was being mapped by the topographers of the Geological Survey, the Agassiz Glacier presumably was a little larger still. It then covered, according to Dyson's map-measurements, an area of about 1.40 square miles; but in the fall of 1940 the two small remnants together had dwindled to only 0.29 square mile, or 21 per cent of the original area.

The thinning of the glacier is perhaps even more impressive. Dyson writes [p. 822]: "Examination of the area from which the glacier has recently retreated indicates that when the ice-terminus lay near the crest of the inner moraine, between 50 and 100 years ago, the ice of the main tongue was several hundred, possibly as much as 700 or 800 feet thick near a site from which the ice has since disappeared. Today it is doubtful if the ice anywhere exceeds 30 or 35 feet in thickness."

That the glacier has continued to disintegrate since Dyson's visit in 1940 is evident from Park Naturalist Walker's description. He found it divided into several sections that are rapidly breaking up and wasting away. Inasmuch as true glacier-motion, on a moderate slope, requires a thickness of ice and firn of not less than 100 feet [chapter on Glaciers, pp. 154-155, in Hydrology (No. 9 of the Physics-of-the-Earth Series), 1942], it may be presumed that the disconnected masses of ice only 30 to 35 feet thick are stagnant and inert. In that condition they are not likely to last many years, unless, indeed, there should be a quick change in climatic conditions.

The amazing rapidity with which the Agassiz Glacier is succumbing to present climatic conditions, as compared with most of the other glaciers in the Park, calls for a special explanation. That explanation is found, at least in part, in the fact pointed out by Mr. Walker, that the lower ice-tongue lies on a fairly steep rock-slope coinciding with the local dip of the strata. As a result the terminus recedes not merely by melting, but from time to time also by the breaking off of sections of ice, which then slide down the incline lubricated by water, and are shattered in the descent. However, as the present writer understands the case, the severance of the glacier into two parts, a few years ago, has done much to hasten its decadence, for, as a consequence, a large proportion of the nourishment of the ice-tongue has been cut off. Formerly the tongue was nourished by many flows of ice converging from different directions into the bowl of the cirque; but today the broad ice-masses in the northwestern part of the cirque, being more strongly insolated than those in the southern and southeastern parts, are depleted to the point of stagnancy and no longer flow down into the cirque-bowl. The tongue therefore is now supplied only by a small flow of ice from the south, and from a once well sustained ice-stream it is reduced to an undernourished glacieret.

Table 1 taken from Mr. Walker's report, summarizes for each of the four glaciers mentioned its variations since 1931 or 1932, the years in which systematic measurements were begun by members of the Park staff.

Table 1--Measured variations of glaciers

(Advance indicated by plus sign and recession by minus sign)

Glacier	Date	Measured change	Cumulative change
		feet	feet
Blackfoot	1932, Aug. 23	[a]	.....
	1933, Sep. 4	+ 64	+ 64
	1934, Aug. 26	- 10	+ 54
	1935, Aug. 23	+ 8	+ 62
	1936, Sep. 17	-104	- 42
	1937, Sep. 21	- 28	- 70
	1939, Sep. 21	- 69[b]	-139
	1940, Sep. 8	- 63	-202
	1941, Sep. 8	-150	-352
	1942, Sep. 5	0	-352
Grinnell	1932, Oct. 6	[a]	.....
	1933, Sep. 14	0	0
	1934, Oct. 5	- 54	- 54
	1935, Sep. 22	- 43	- 97
	1936, Sep. 20	- 64	-161
	1937, Oct. 25	- 4	-165
	1938, Oct. 6	- 76	-241
	1939, Sep. 19	- 34	-275
	1940, Sep. 10	- 71	-346
	1941, Sep. 9	-105	-451
	1942, Sep. 7	0	-451
Sperry	1931, Oct. 11	[a]	.....
	1932, Sep. 14	.....	[c]
	1933, Sep. 7	.....	?
	1934, Aug. 28	[d]	?
	1935, Sep. 9	.....	.....
	1936, Sep. 18	- 97	- 97
	1937, Sep. 17	- 29	-126
	1939, Sep. 10	-281[b]	-407
	1940, Aug. 29	- 33	-440
	1941, Sep. 4	- 45	-485
	1942, Sep. 4	- 21	-506
Agassiz	1932, Aug. 28	[a]	.....
	1934, Sep. 28	- 75[b]	- 75
	1935, Aug. 28	- 79	-154
	1936, Sep. 3	-465	-619
	1938, Sep. 28	- 35[b]	-654
	1942, Sep. 9	-2276[e]	-2930

[a]Markers set. [b]Two years. [c]Advance not measured. [d]Markers set at new location. [e]Four years.

Glaciers of Rocky Mountain Park, Colorado

Andrews Glacier, according to Park Naturalist H. R. GREGG's report, in September, 1943, was in "healthier" condition than in September, 1941, when it reached an extreme point of depletion. Heavy snow-precipitation during the winter of 1941-42 and cool weather during the succeeding melting season combined to rebuild the glacieret somewhat.

No measurement directly in line with the glacier's axis is possible, owing to the existence of a mud delta and a lake at its front: therefore no precise figure of advance can be given. As in previous years it was found best to measure at an angle to the axis from a rock on the north side of the cirque, and that measurement in 1942 showed an advance of about five feet. Taken as a whole, the glacieret appeared to have changed only slightly.

Tyndall Glacier also appeared to have been benefitted by the heavy snow-precipitation and low temperatures. The photographs submitted by Mr. Gregg show the glacieret more broadly mantled with snow than in previous years. The bergschrund at the top was largely masked by snow, and extensive snow-fields on and around the terminus prevented accurate determination of the position of the ice-front. As the snow-fields reached forward as far as the station from which the measurements are usually made, the distance to the front is reported as being zero; but it is realized

that this does not afford a true measure of the advance which the ice-body under the snow may have made. In 1940, the last year in which a measurement was made, the ice-front lay 56 feet from the station. It does not seem likely that the ice-body could have advanced so great a distance in two years.

The Andrews and Tyndall glaciers continue to be of peculiar interest to glaciologists as vestigial remnants of largely wind-fed cirque glaciers that originated presumably during the "little ice-age" of the last 3,000 to 4,000 years.

Glaciers of Sierra Nevada

In conformance with the policy adopted by the Park Naturalist's staff in 1941, no attempts were made in 1942 to measure the recession of any of the glaciers in or adjacent to Yosemite National Park, it being realized that the true frontal margins of those glaciers are invisible, being concealed by accumulations of morainal debris. On the other hand, efforts were made, as in the preceding year, to determine the changes in thickness which the two lobes of the Lyell Glacier, the most important ice-body in the Park, had suffered during the past 12 months. In addition, photographs were taken of the Lyell, Maclure, Dana and Conness glaciers, from stations occupied with the camera in previous years. Such photographs, taken systematically every year, are proving to be of value in comparative studies of the gradually changing configuration of the glaciers.

To measure changes in the thickness of the two lobes of the Lyell Glacier, the profile-lines across the two lobes, laid out in 1933, were once more resurveyed. This was done, as before, by taking vertical-angle sights with an Abney hand-level from the fixed stations at the ends of each profile to points on the surface of the glacier, the distances to those points being measured with a steel tape. The elevation at each point then is computed trigonometrically. Three points were thus determined on the West Lobe and two points on the East Lobe.

The results indicate that on October 4, 1942, the surface of the West Lobe at a point 311 feet from the eastern end of the profile had been lowered 2.8 feet, and at a point 714 feet from the same station it had been lowered 6.2 feet. The second point lies about two-fifths of the total distance across the West Lobe, and the reduction of 6.2 feet is therefore probably representative in a general way of the change that has taken place over the central portion of the glacier. This is a matter of no little interest, in view of the fact that the snowfall during the winter of 1941-42 was decidedly in excess of normal. If in the summer of 1942 the glacier lost six feet in thickness, in spite of excessive snowfall during the preceding winter, one may well wonder how much it would lose after a normal winter's snowfall.

The table at the end of Mr. Brockman's report shows that during the period 1933-40 the surface of the glacier at the first point mentioned was lowered 17.2 feet by ablation, that in 1941 it was raised 2.8 feet by heavy snowfalls, and that in 1942 it was again lowered 2.8 feet. The net loss in thickness for the period 1933-42 therefore is 17.2 feet. At the second point, nearer the middle of the glacier, the surface was lowered by ablation 26.4 feet during the period 1933-40, in 1941 it was raised by snowfall 12.5 feet, and in 1942 it was again lowered 6.2 feet. The net loss in thickness for the period 1933-42 therefore is 20.1 feet. Two years of excessive snowfall, it thus appears, have not rebuilt the glacier, but have only slowed up its decline.

The East Lobe in 1942 fared better than the West Lobe, for the measurements indicate no noteworthy change in the level of its surface. Evidently the losses by ablation during the summer just balanced the increments that had been made by the heavy snowfalls during the winter. It does not follow, however, that all of the winter's snow had been removed by the end of the melting season. On the contrary, as is clearly shown by the excellent photographs that accompany Mr. Brockman's report, the East Lobe on October 4 was still in large part mantled with snow, old ice appearing at the surface only in restricted areas. On the whole, the glacier more than held its own as the result of the excessive snows.

The tabulation at the end of Mr. BROCKMAN's report shows that at a point 504 feet from the eastern end of the profile the surface of the glacier was lowered by ablation 22.3 feet during the period 1933-40, and that it has remained unchanged through 1941 and 1942. At a point 768 feet out, nearly one-third of the distance across the glacier, the surface was lowered 38.8 feet during the period 1933-40, and since then it has remained unchanged. The net loss in thickness for the period 1933-42 therefore is 22.3 feet at the first point and 38.8 feet at the second point. At a third point, just beyond the middle of the glacier, a net change of 35.7 feet was determined. In the case

of the East Lobe, therefore, as in the case of the West Lobe, two years of excessive snowfall have only served to halt the progressive thinning of the ice-mass. They have failed to build it up.

Whether the points to which measurements were made lay all on the snow-covered part of the glacier, or whether any of them lay on patches of exposed ice, Mr. Brockman's report does not state. If they all lay in the snow-covered area and yet showed no increase in the glacier's thickness, then some explanation seems called for. It is possible, of course, that the method of determining elevations with an Abney hand-level is not accurate enough to indicate small changes, but, aside from that, there is another possible cause that deserves to be considered. This is the more or less constant shrinkage which a glacier normally suffers as a result of (1) the progressive compaction of the névé, (2) the expulsion of air, (3) the recrystallization of the coarse glacier-ice in the lower layers, and (4) the losses of ice through friction and melting at the rock-bed.

It is not generally realized that glaciers are in a state of constant shrinkage, but the fact is familiar to glaciologists. The actual rate at which such shrinkage takes place, however, has never been determined, so far as the writer knows. It could be determined, for a given glacier, under circumstances such as occurred on the two lobes of the Lyell Glacier in 1942--namely, by measuring the thickness of the snow-mantle at points where accurate measurements show that the glacier's surface had remained unchanged in height. At such points the thickness of the snow-mantle would exactly counterbalance the shrinkage of the glacier during the past twelve months and would afford a close measure of that shrinkage unless, indeed, some surface ablation had taken place after the measurements of the preceding year and before the first snowfall.

Glaciers of Mount Hood, Oregon

The following data are taken from the annual report of the Research Committee of the Mazamas, submitted through its chairman, KENNETH N. PHILLIPS.

Eliot Glacier, which has been the principal subject of investigations by the Mazamas since 1925, was visited again in September, 1942, and was found to have receded 25 feet since it was measured in 1941. As the terminus lies in a steep and narrow gulch, where direct measurements would be difficult to make, the recession was determined by triangulation, as in previous years. In 1941, the glacier receded 19 feet, in 1940 it receded 18 feet, and in 1939 it receded 64 feet.

Coe Glacier, on the north side of the peak, has receded 41 feet since September, 1941. The terminus was clearly defined and crescent shaped in plan, the stream issuing from it at a point 27 feet back from the projecting horns of the crescent.

Ladd Glacier, which had not been visited since August, 1936, had receded 84 feet during the intervening six years. Under approximately uniform conditions this would imply a mean recession of 12 feet per year.

Reduction of Eliot Glacier by surface-ablation--In 1940 the Research Committee of the Mazamas laid out by transit-and-stadia survey two profile-lines across the lower half of the Eliot Glacier, the purpose being to determine by resurveys from time to time the rate at which the glacier's surface is being lowered by ablation. The first resurvey was made in September, 1941, and the second in September, 1942, the dates being chosen as nearly as practicable 12 months apart. In the carrying out of this program LOUIS E. RYDELL, of the Mazamas, has been particularly active, and to him largely should go the credit for the results obtained. So instructive are these results that it seems worth while to present them somewhat fully.

The upper half of the Eliot Glacier descends from the steep cone of Mount Hood by successive, intricately crevassed ice-cascades across which it is impossible to run any survey-lines: but the lower half, near the base of the peak, has a relatively moderate gradient and is rent only by occasional crevasses. It is across this lower portion of the glacier, which is flanked by high lateral moraines, that the profile-lines have been surveyed. The lower, or A-line, crosses the glacier about 1,000 feet above the terminus; the upper, or B-line, crosses it half a mile farther up. Both lines reach from one moraine-crest to the other, their end points on those ridges being marked by red paint on stable boulders.

The A-line has a total length of 1,026 feet, but only its central portion, 800 feet long, is over glacier-ice, the outer portions extending over the slopes of the moraines. No ice is actually visible at any point in the central stretch, the glacier's surface being covered by a continuous mantle of morainal debris, but the presence of ice under that debris is unmistakably indicated by the fact, developed by the resurveys, that the surface is constantly being lowered by ablation. The

flanking moraines, on the other hand, remain unchanged from year to year. The central 800-foot stretch therefore affords a minimum measure of the width of the glacier.

The discovery that on this part of the glacier ablation is effective, in spite of the insulating mantle of debris, is itself a matter of some interest, as the debris is already thick enough to permit vegetation to grow on it--scattered clumps of grasses and sedges, and a few bushes (at most two feet high), of alder, willow, heather, and white-bark pine. The measurements show that the ablation-losses increase gradually from nearly zero at the ends of the 800-foot stretch to a maximum of about five feet per year at the middle. Over a stretch of 700 feet they average three feet per year. The reason for this gradual increase in ablation-losses towards the middle is, primarily, that the debris-mantle thins progressively from the margins inward, and secondly, to judge from photographs, that the melt-water rivulets on the glacier converge to a central streamlet that at times attains considerable eroding power. The cumulative effect through the years is seen in the strongly concave form of the profile, which resembles that of a valley. At the middle it is, by actual measurement, 70 to 75 feet lower than at the ice-margins, and 108 to 130 feet lower than the crests of the moraines.

At the B-line the glacier is less heavily mantled with debris and as a consequence the ablation-losses there are much greater. The B-line is 1,571 feet long from moraine-crest to moraine-crest; about 1,100 feet of it is over glacier-ice, and 630 feet of it, near the middle, is over bare ice. In that central stretch, naturally, ablation is most rapid, the losses amounting to 15 feet per year, or three times the maximum measured on the A-line. Over the adjacent stretches of debris-covered ice they average 6.5 feet per year, or fully twice the amount measured on corresponding stretches on the A-line. The cumulative effect through a period of years has been, as might be expected, to give the glacier at the B-line a much more deeply concave profile than at the A-line. At the middle, indeed, the B-profile sags fully 250 feet below the margins of the ice-mass and not less than 330 feet below the crests of the lateral moraines. As a consequence the general effect produced is, anomalously, like that of an ice-floored canyon.

Concave glacier-profiles such as these differ widely from the gently convex profiles that are commonly regarded as characteristic of glacier-tongues. It is to be borne in mind, however, that the prevailing conception of convexity is based largely upon observations on fairly clean glaciers, such as occur on mountains composed of hard, crystalline rocks that break down slowly and furnish relatively little debris. Glaciers on peaks composed of crumbling volcanic rocks, such as the Eliot Glacier on Mount Hood, on the other hand, become heavily encumbered with frost-loosened rubble, most heavily so at their margins, and in such glaciers a convex profile can exist only at times of what may be termed glacial prosperity. At such times the losses by surface-ablation are balanced, or exceeded, by replenishing ice-flow from above. Although ablation-losses are greatest in the medial lane of cleanest ice, it is precisely there, as a rule, that the ice-flow is strongest and most competent to replace the losses. Once such an era of prosperity begins to wane, however, and replenishment by the ice-current no longer makes good the losses by ablation, such a glacier will gradually lose its convex profile and eventually will acquire a concave one. And with continued reduction, always greatest at the middle, the concavity of the profile will become ever more accentuated, as is vividly illustrated at present by the Eliot Glacier.

The final stage is reached when the glacier is reduced to less than the minimum thickness required to induce plastic flowage in the basal layers of the ice. That minimum thickness appears to be between 100 and 150 feet, depending upon such variable factors as angle of slope, friction on the rock-bed, climatic conditions, and internal temperature [F. E. Matthes, Glaciers, chapter V in Hydrology (No. 9 of the Physics-of-the-Earth Series), pp. 154-155 and 181-182, 1942]. What remains of the ice-mass then becomes stagnant and in the course of time buried under accumulating rock-debris.

Bodies of such buried "dead ice," partially revealed by sharp stream-erosion or gullying rains, have been discovered on the flanks of Mount Hood and Mount Shasta. A. H. SYLVESTER, of the Geological Survey, who mapped Mount Hood in 1906, reported finding large masses of old glacier-ice exposed to view by the erosion of a narrow trench in the bottom of White River Canyon, on the south flank of the peak. They had been preserved by layers of morainal and alluvial material 75 to 200 feet in aggregate thickness. Some idea of the age of this entombed ice may be gained from the fact that about half way up in this deposit there is a layer of black soil containing upright stumps and fallen logs of an ancient forest [A. H. SYLVESTER, Is our noblest volcano awakening to new life?, Nation. Geog. Mag., v. 19, pp. 518-520, 1908].

In the ravines that furrow the slopes of Mount Shasta, OLIVER KEHRLEIN, Chairman of the Committee on Glacier Studies of the Sierra Club, in 1934 and 1935 found buried glacier-ice

exposed in newly cut torrent gullies. This old ice extended down the mountain for distances of more than one mile below the termini of the existing glaciers [F. E. Matthes, Reports of Committee on Glaciers, 1934-35 and 1935-36, Trans. Amer. Geophys. Union, p. 390, 1935, and pp. 287-288, 1936].

That the Eliot Glacier has not yet reached the final stage of stagnancy is shown by the movement of the ice which Messrs. Phillips and Rydell have measured at each of the two profile-lines in 1941 and 1942. At the middle of the B-line their measurements indicated a maximum movement of 16 feet in two years, the average for the entire profile being 11.5 feet. At the A-line, which is only 1,000 feet distant from the terminus, the maximum movement amounted to only 9.5 feet in two years and, over a stretch of 700 feet, the movement averaged 7.7 feet. At the terminus cryocinemeter-measurements, on September 20, 1942, indicated a forward movement of 0.06 inch in a period of eight hours. That rate, if continued for a whole year, would move the terminus forward 5.5 feet, which is more than the movement measured at the middle of the A-line (4.75 feet). However, the cryocinemeter-measurements were made in the daytime (from $08^h\ 45^m$ a.m. to $04^h\ 45^m$ p.m.), when the movement is more rapid than it is at night, and in the month of September, when the movement doubtless averages more than it does in winter. The rate indicated by the cryocinemeter therefore is doubtless greater than the mean for the year.

Comparison of the present rate of movement at the A-line with the rate which the Mazamas measured on the same part of the glacier during the period 1925-28, reveals that the movement has slowed up considerably during the intervening 15 years. During the period 1925-28 the maximum movement in mid-glacier averaged 10.3 feet per year, but by 1942 it had been reduced to less than one-half, namely, to 4.75 feet. This slowing up is, no doubt, a concomitant effect of the progressive thinning of the glacier by ablation; for the plasticity of the ice in the lower layers is a function--an exponential function, presumably--of the pressure on them, and therefore of the glacier's thickness. As the glacier grows thinner, therefore, the rate of movement decreases at a relatively high ratio.

The present thickness of the Eliot Glacier can be estimated only roughly. Phillips in his report suggests that near the A-line it may be anywhere between 50 and 150 feet, and at the B-line about 100 feet more, those estimates being based on assumed gradients of the glacier's bed. However, it is possible to go a bit further and to assert that the glacier is not less than 100 feet thick at any point in its lower course; for, as the measurements have shown, it is actively moving, even at the terminus, which is its most sluggish part, and movement by plastic flowage in the lower layers requires, as already pointed out, a minimum thickness of ice of more than 100 feet. It seems entirely probable, therefore, that the Eliot Glacier is at present still between 100 and 150 feet thick at the A-line, and as much as 250 feet thick at the B-line.

Taking these approximate figures as a working basis, some estimates may next be made of the time in which the lower half of the Eliot Glacier is likely to be destroyed by ablation. There is, of course, no certainty that ablation will continue during the decades to come at the rates that prevailed in 1941 and 1942, for those years were unusually warm and dry, as compared with the average during preceding decades (according to meteorological records at Portland, Oregon, the weather station nearest to Mount Hood). On the other hand, it is evident from the continued and accelerated recession of many glaciers in the Pacific Northwest during past years, that the general trend of climate there is towards warmer and dryer conditions. In the absence of indications to the contrary, therefore, it may reasonably be supposed that that trend will continue for some time to come. All things considered, then, estimates based on the ablation-measurements of 1941 and 1942 may not go altogether wide of the mark, and in any event will serve to indicate a minimum period.

The problem is, however, complicated by the fact that some parts of the Eliot Glacier are wasting away much more rapidly than others. The bare ice at the B-line is melting three times as fast as the debris-mantled ice at the A-line. A simple calculation indeed, suggests that the ice in the vicinity of the B-line, in spite of its greater thickness, may be destroyed long before that in the vicinity of the A-line.

At the B-line the maximum rate of ablation is 15 feet per year. If, therefore, the ice there is 250 feet thick, it may melt away completely in 17 years. More probably, however, it will take a longer time, for the ice which is now bare is bound to become mantled with rock-debris. At the A-line the maximum rate of ablation is only five feet per year. At that rate the estimated thickness of 100 to 150 feet will be reduced to zero in 20 to 30 years. There, however, the rate will slow down also as the debris-mantle grows thicker. It may eventually be reduced to less than one foot per year, and the terminal portion of the glacier may therefore remain in existence for sev-

eral decades. However crude these calculations may be, they leave little doubt that the cleaner part of the glacier near the B-line will be destroyed long before the debris-covered part near the A-line. The latter, indeed, will probably survive for some time as an isolated mass of debris-cloaked "dead-ice" resembling an ill-shaped terminal moraine.

Glaciers of Mount Rainier, Washington

The following data are taken from a brief report by HOWARD R. STAGNER, Park Naturalist of Mount Rainier National Park.

Nisqually Glacier in September, 1942, appeared to have receded only two feet in 12 months. This small amount contrasts strikingly with all recessions recorded in previous years. For the period 1918-31 the average was 70.7 feet per year and for the period 1931-41 it was 79.2 feet per year. The smallest recession previously reported by the National Park Service, in 1927, was 43 feet.

The explanation for this abrupt change in the rate of recession is, at the time of this writing, still uncertain. A nearly normal amount in any event, would seem more in keeping with the reduction by surface-ablation which the glacier has suffered since the fall of 1941 (see below).

For the South Tahoma Glacier an advance of 45 feet is reported, but this advance, Mr. Stagner explains, occurred only at the point where the stream formerly issued, and is not to be regarded as representative of the terminus as a whole, which presumably is constantly receding. The lower portion of the South Tahoma Glacier is encumbered with much morainal debris and does not present a clean-cut ice-front to which measurements can conveniently be made. It has therefore been found expedient, in past years, to measure to the ice that is exposed at the portal from which the stream escapes. Melting there, however, appears to have been accelerated by the presence of the stream, and as a consequence the recession-figures reported in recent years have been excessive. They have ranged from 67 feet in 1930 to 224 feet in 1941. In 1942, however, it was found that the stream had shifted its course under the glacier and issued from a new portal on the southeast side of the terminus. At the old portal, in consequence, the excessive melting had ceased and instead, the ice had advanced somewhat.

So largely obscured by debris is the lower end of the South Tahoma Glacier, that its recession probably will always be difficult to determine with accuracy. It is hoped, nevertheless, that measurements to it will not be discontinued for that reason. The results obtained from year to year may sometimes seem inconsistent with each other, but in the long run they will afford an index of the glacier's behavior.

Emmons Glacier in 1942 appeared to have receded 72 feet. That amount harmonizes with the recessions reported in previous years, though at the terminus of the Emmons, as at that of the South Tahoma, accurate measurements of recession are hardly possible, owing to the presence of large quantities of morainal debris. The recession in 1942 compares with 89 feet in 1941, 97 feet in 1940, 57 feet in 1939, and 107 feet in 1938.

Carbon Glacier is less heavily loaded with debris than the preceding glaciers and therefore is easier to measure. In 1942 it receded 45 feet, as compared with 54 feet in 1941, 46 feet in 1940, 25 feet in 1939, and 18 feet in 1938.

The broad front of Paradise Glacier in 1942 receded relatively little and in some places not at all, in contrast to the large recessions noted in 1941. At its northwestern part it receded only 15 feet, as compared with 80 feet in 1941; and at its southeastern part it remained practically unchanged, whereas in 1941 the ice there melted back 202 feet. This sharp decrease in the recession of the Paradise Glacier Mr. Stagner attributes chiefly to the fact that in 1942 the glacier's surface remained in large part covered with snow until late in the summer.

To the foregoing report on the state of the five representative glaciers on Mount Rainier that are measured annually by the National Park Service are to be added the following data on ablation-losses on the lower part of the Nisqually Glacier, determined by the Geological Survey.

In 1942, according to the report of ARTHUR JOHNSON, Hydraulic Engineer of the Geological Survey, no complete resurvey by plane-table and stadia was made, but the two profiles across the Nisqually Glacier that had been laid out in 1930 and resurveyed in 1941, were resurveyed once more. The results are of peculiar interest in that they show that under certain conditions some

parts of this glacier's surface, in a given cross-profile, may remain unchanged in elevation, wh. adjacent parts are lowered appreciably by ablation.

On the lower profile, which crosses the glacier about 3/4 mile above the terminus, at a mean altitude of 5,250 feet, 12 points were determined from a bench-mark on the left lateral moraine. It was found that from a point 500 feet from the bench-mark to another 1,000 feet distant, the glacier's surface had remained essentially unchanged in elevation since 1941: but throughout the next stretch of 450 feet the surface had been lowered 20 to 25 feet. Beyond that central stretch, again, and as far as the western margin of the glacier, 2,000 feet distant from the bench-mark, the surface was practically unchanged.

This disparity between the central strip of ice in the glacier and the two flanking strips was much greater in 1942 than in 1941. The resurvey of 1941 disclosed that in the eleven years that had elapsed since 1930 the western strip had been lowered 20 feet, while the central strip had been lowered 100 feet. The average reduction per year, therefore, had been 1.8 feet in the western strip, and 9.1 feet in the central strip. But the resurvey of 1942 revealed that while the western strip had remained practically unchanged, the central strip had been lowered 20 to 25 feet in a single year.

On the upper profile, which crosses the glacier 1-1/4 miles above the terminus and at a mean altitude of 6,000 feet, 17 points were determined from a bench-mark on the left lateral moraine. In 1941 only eight points were determined on this profile, hence the results of the two surveys are not closely comparable. However, making allowance for that difference, it appears that by 1942 the eastern part of the glacier's surface, 1,000 feet wide, had been lowered only slightly, while the central strip, 700 feet wide, had been lowered 15 feet. The western strip, about 100 feet wide, again, showed no significant change. On the whole, the state of things on this profile was more nearly normal in 1942 than it was in 1941, when the eastern half of the glacier's surface had risen 30 feet, while the western half had been lowered in places as much as 70 feet since 1930.

This apparently incongruous behavior of the eastern and western halves of the glacier at the upper profile has not yet been fully explained, but is probably due to the fact that the main ice-current is not in the middle of the section but in the eastern half.

Mr. Johnson adds that in 1942 a third profile was laid out across the glacier at a distance of 1.9 miles from the terminus and at an approximate mean altitude of 6,750 feet. It is situated just below the confluence of the Wilson Glacier, which is the Nisqually's main tributary on the west side. The changes that take place at this profile will, it is believed, indicate what changes may be expected to occur later in the lower course of the glacier; and they will probably throw light also on the regimen of the glacier in this higher altitude-zone, where the meteorological conditions are quite different from those in the lower zones.

Glaciers of Alaska

In 1942 no expeditions were made to Alaska for the purpose of measuring glaciers, but in that year the United States Geological Survey published a bulletin containing some interesting information concerning the recession of the Portage Glacier, which blocks a much traveled pass across the mountains to the west of Prince William Sound. That publication is F. F. BARNES' report on the geology of the Portage Pass Area, Alaska [U..S. Geol. Surv. Bull. 936-D, pp. 211-235, 1942]. The recession-data were obtained in the course of an investigation by the Alaska Railroad, in cooperation with the Geological Survey, the object of which was to determine the feasibility of constructing a railroad to connect the present line at the head of Turnagain Arm with tide-water at the head of Passage Canal. As the data are based in large part on accurate surveys, and cover a period of 41 years, they merit being recorded here.

Portage Pass is a deep, broad-floored valley 12 miles long and only about 100 feet above sea-level, that separates the ice-capped Kenai Peninsula to the south, from the glacier-bearing Chugach Mountains on the mainland to the north. Were the Pass unobstructed, it would afford an easy route of transportation across the neck of the peninsula, and a railroad laid through it would greatly shorten the haul from Anchorage, in Cook Inlet, to Valdez, on Prince William Sound. It would, moreover, permit coal to be shipped by rail from the Matanuska field directly to an ice-free harbor on Prince William Sound. However, the Pass is blocked at the middle by the Portage Glacier, which descends into it from the Kenai Mountains, and in addition by Portage Lake, a deep body of water that extends from the glacier's front to the foot of the steep mountains on the

north side. The building of a railroad through the Pass consequently is not feasible, and the only alternative appears to be a location through the rugged mountains to the north of the Pass--a project that would involve considerable tunneling.

The historical data, meanwhile, show that, in spite of the obstructing glacier, Portage Pass has been much used as a route of transportation in times past. Captain GEORGE VANCOUVER in 1794 learned that the Pass then already had long been used by Russian and Indian fur-traders. The glacier, although it filled the valley for a distance of several miles, offered no formidable obstacle to travel with sleds in winter, when its surface was covered with deep snow, but in summer it was shunned, as the gaping crevasses then constituted a serious hazard. However, there was no need of traversing the Pass in summer, as Cook Inlet then is free of ice, and ships can readily travel through it and around the Kenai Peninsula.

From the accounts of the successive explorations and surveys that have been made in this part of Alaska it is apparent that Portage Pass has been completely blocked by the glacier ever since it was discovered by white men, early in the eighteenth century. W. C. MENDENHALL, of the Geological Survey, who accompanied Captain E. F. GLENN's expedition, found the Pass thus blocked in 1898, and in his report he gave the first estimates of the dimensions of the ice-barrier. "A glacier covers four or five miles of the isthmus," he wrote, "and its highest point is 1,000 or 1,100 feet above the sea, with a steep approach from the east. This climb is the only serious obstacle to the portage, and in order to surmount it with heavily loaded sleds it is usually necessary to resort to a system of ropes and pulleys" [W. C. Mendenhall, A reconnaissance from Resurrection Bay to the Tanana River, Alaska, in 1898, U. S. Geol. Surv. 20th Ann. Rep., pp. 300-301, 1900].

In 1913 C. E. GIFFIN, of the Geological Survey, made the first contour-map of the Portage Pass Area. That map [Plate 2, in Mineral resources of Alaska, 1913, by A. H. Brooks and others (Bull. 592, 1914)] shows the Pass filled with ice over a distance of 2-3/4 miles. The Portage Glacier at that time split into two lobes, the major of which extended for two miles in a northwesterly direction, while the minor one, 3/4 mile long, drained northeastward in the direction of Passage Canal. The main lobe not only filled the whole width of the Pass but even pushed one-half mile up into the tributary valley of Placer Creek, on the north side. Essentially similar conditions prevailed in 1914, as is evident from the more detailed map of the Pass made in that year by W. C. GUERIN and R. J. WEIR, of the Alaskan Engineering Commission.

No further surveys were made until 1939, when the engineers of the Alaska Railroad made their map for the location of the tunnel-route. That map [Plate 13, in Barnes' report] indicates the first significant reduction in the size of the Portage Glacier. It shows that in 1939 the major lobe no longer reached the mouth of the valley of Placer Creek and had withdrawn a distance of 1,500 to 2,200 feet from the foot of the mountains on the north side of the Pass. At its western margin the ice-front had retreated 4,000 feet from the farthest point which it reached in 1914. In the valley-area thus vacated by the ice lay a lake about one mile long and on an average 3,000 feet wide. That lake, soundings have revealed, attains at the glacier's front a maximum depth of 400 feet. Its bottom there was fully 300 feet below sea-level.

The northeastern lobe of the Portage Glacier in 1939 had almost disappeared, and the entire ice-mass, from the point where it enters the valley down to the end of the northwestern lobe, had lost at least 200 feet in thickness. Patches of fresh, unweathered gravel clinging to the flanking mountains, indicate definitely the measure of that reduction.

From a comparison of the maps and photographs of the survey of 1939 with those of the surveys to 1913 and 1914 it is evident, further, that all the other glaciers in the vicinity of Portage Pass have likewise shrunk considerably in length and in thickness during the intervening quarter-century. The Whittier Glacier, which lies to the east of the Portage Glacier, in 1913 emerged from a hanging valley and reached down the mountain side to an elevation of about 600 feet; but by 1939 it had been shortened, by estimation, at least one-quarter mile, and was only barely visible at the mouth of the hanging valley, which has an elevation of 1,000 feet or more.

Learnard Glacier, a narrow ice-tongue that occupies a steep gulch in the flank of the Chugach Mountains and drains into the head of Passage Canal, appears to have receded about 1,500 feet since 1914. The history of the Learnard Glacier, however, can be traced further back than 1914. In 1898 Mendenhall found the ice-front about one-quarter mile back of a hillock that stands, isolated, on the alluvial floor of the Pass. Giffin's map of 1913 shows the glacier about the same distance from that hillock. It may be presumed, therefore, that the glacier made no noteworthy

advances or retreats during the intervening 15 years; also, inasmuch as it deposited no distinct moraine at any point, that its front oscillated gently back and forth during that period. The hillock, however, tells of still earlier events. Mendenhall describes it as "a hillock 220 feet high and one-half mile long, situated with its longer axis parallel to the ice-front" [loc. cit., pp. 325-326]. He first supposed it to be a simple terminal moraine, but upon closer examination he found it to consist of a mass of ice mantled with rock-debris and containing such debris disseminated through it. He therefore recognized it as a remnant of the terminal portion of the glacier itself, partially preserved by reason of the protective effect of its debris-mantle, while the cleaner ice farther back in the glacier, lacking such protection, had melted away. And he inferred that the hillock stood at a point where the ice-front had rested for some time, long enough to become covered with rock-debris released by the melting ice.

To this may well be added that the hillock undoubtedly indicates the farthest limits of the glacier's last major advance. The heavily loaded condition of the terminal portion indicates that there had been a considerable advance, overriding and picking up quantities of rock-debris left during a preceding recession. The date of the advance is not known, and is likely to remain a matter of conjecture until more information is at hand concerning glacier-oscillations in this part of Alaska prior to 1898; nevertheless, there are a few facts upon which a rough estimate can be based. The rate at which the debris-covered ice-hillock has been reduced since 1898 affords a clue. In 1898 the hillock was 220 feet high at the highest point; by 1914, as is indicated by the survey of that year, it had been reduced to a maximum height of 170 feet; and by 1939, according to Barnes' report, it had almost disappeared, "its site being occupied by low heaps and ridges of coarse blocks, at most 70 feet in height ..... By 1939 probably no ice remained under the debris" [F. F. Barnes, Geology of the Portage Pass Area, Alaska, U. S. Geol. Surv. Bull. 926-D, p. 231, 1943].

The rate of reduction, averaging three feet per year from 1898 to 1914 and four feet per year from 1914 to 1939, is, in fact, remarkably rapid for a debris-covered ice-mass and strongly suggests that the debris-mantle was thin or, at least, not sufficiently dense to effectively insulate the ice from the heat of summer. The fact that the rate increased through the years from three to four feet, instead of decreasing, as normally occurs in such cases owing to the gradual thickening of the debris-mantle, need not be accorded much significance, for the earlier measurements probably were less accurate than the later. The increased rate after 1914, nevertheless, may well be a real thing due to rising temperatures, for, as already shown, it was during the period 1914-39 that the Portage Glacier and its neighbors suffered the most conspicuous reduction in length and thickness. However that may be, the practically complete destruction of the ice-hillock in only 41 years or less, in spite of its protective covering, argues against the probability of its having any great antiquity. Its height in 1898 was, of course, not indicative of its initial height. The mass must have been reduced considerably during the time that the cleaner ice farther back on the glacier was melting away; but that melting need not have required many decades, inasmuch as ablation of clean ice in those latitudes often proceeds at rates of six to more than ten feet per year. If that part of the glacier was 300 to 400 feet thick, it may have been destroyed, given appropriate conditions, in 30 to 60 years. This rough estimate, accordingly, would seem to indicate that the glacier's advance culminated in any event at some time during the nineteenth century, possibly as late as during the second half.

In a problem of this kind, the concept of the "little ice-age" as a distinct period of glacial activity whose climactic phases occurred during the period of modern history, is most helpful. It precludes at once any thought that the debris-covered ice-mass left by the retreating Learnard Glacier might date from the end of the Pleistocene ice-age, and leaves no doubt that the ice-mass was a product of a modern glacier-advance--the latest, and one of the greatest, of the several that have occurred during recent centuries. The concept of the "little ice-age" and of the thermic period that preceded it during the middle part of post-Pleistocene time are based, it is true, primarily on European data, and their applicability to distant Alaska therefore may perhaps be questioned. The fact recognized by all recent explorers is, however, that the reality of those two contrasting periods is nowhere more abundantly and more impressively attested than in Alaska [F. E. Matthes, Glaciers, chapter V in Hydrology (No. 9 of the Physics-of-the-Earth Series), pp. 200-201, 208-209, 1942]. Many of the larger Alaskan glaciers have within the last few centuries invaded mature forests containing trees hundreds of years old--climax forests, in the ecologic sense, that must have been in existence continuously for a thousand years at the very least. And in the Glacier Bay Region the recession of the ice is uncovering the unfossilized stumps of such a forest that evidently extended over a vast area and flourished for a long time [W. S. Cooper, The problem of Glacier Bay, Alaska, Geog. Rev., v. 27, pp. 37-62, 1939]. There is thus indubitable evidence, on the one hand, of a moderate recrudescence of glacial conditions for several centuries past, and, on the other hand, of a preceding period of widespread deglaciation and luxuriant forest-growth.

As to individual glacier-oscillations during the "little ice-age," it can hardly be supposed that those in Alaska synchronized closely with those in the Alps or in Norway. Advances and recessions of Alaskan glaciers are notoriously diverse and sometimes in opposite phase, as the result of varying local factors. But there is good reason to believe that the general pattern of alternating advances and recessions was about the same in Europe and in Alaska. And there is also good reason to believe that in both Europe and Alaska the last pronounced glacial maximum of the "little ice-age" occurred at some time about the middle of the nineteenth century. That last glacial maximum, then, in all probability was recorded in the recently destroyed hillock at the front of the Learnard Glacier.

U. S. Geological Survey,
Washington, D. C.

REPORT OF THE COMMITTEE ON TRANSPIRATION AND EVAPORATION, 1942-43

H. G. Wilm, Chairman
C. W. Thornthwaite, Assistant Chairman

E. A. Colman	S. T. Harding	C. H. Lee
N. W. Cummings	A. H. Hendrickson	C.-G. Rossby
A. R. Croft	I. E. Houk	T. Saville
H. T. Gisborne	J. Kittredge	C. A. Taylor

Because of the recency of his appointment, the Chairman was unable to obtain reports from all members of the Committee. Accordingly the following statements form only a partial summary of current work known to the Committee in the field of transpiration and evaporation.

E. A. COLMAN (California Forest and Range Experiment Station)--The Committee reports appearing in the Transactions of 1940 and 1941 raised some questions quite fundamental to the research in which many of us are engaged, that is, the measurement of evapo-transpiration water-losses under natural watershed-conditions and in lysimeters. Both reports indicate considerable differences of opinion and show that little research has been done toward improving lysimeter-design and toward comparing lysimeter-results with those obtained under natural conditions. We are particularly concerned with the problem of operation of lysimeters on the San Dimas Experimental Forest and are now engaged in studying lysimeter-data collected through the last six years from this point of view.

The San Dimas lysimeter-installation, because of the diversity of its lysimeter-types, is singularly well suited to a study of how these instruments function and how closely any of them approximate conditions in field-soils. It consists of two groups of weighing-type tanks containing 300 and 1600 pounds of soil, respectively, large concrete lysimeters holding about 70 tons of soil, and a group of pits (the so-called "unconfined lysimeters") each of which contains approximately 35 tons of soil. The lysimeters listed are 2, 3, 6 and 6 feet deep, respectively, and their corresponding surface-areas are 250 square inches, 1000 square inches, 218 square feet, and 109 square feet. In the first three groups the soil rests on or against perforated drainage-plates, while in the unconfined lysimeters there is direct soil-to-soil contact at the bottom. All groups of lysimeters are provided with the same kind of soil and have been subjected to the same vegetation treatment.

By comparing the data on soil-water content (both total water-content and moisture-distribution), water-yield data, evapo-transpiration losses, and annual plant-growth and yield-information, in the several groups the relationships existing between lysimeters having different depths, surface-areas, and drainage-characteristics will be shown. A preliminary analysis of the data indicates that the usefulness and limitations of the several types of lysimeter will be made clear and that suggestions for the modification of existing installations can be made.

Observation of performance of lysimeters during the past six years has shown that the following points should be stressed in any lysimeter research program which has utilization of water as an objective:

(1) Accuracy of measurement of precipitation reaching the soil-surface
(2) Allowance of preliminary period sufficiently long to insure the attainment of structural stability in the enclosed soil-mass
(3) The incorporation of a calibration-period during which all lysimeters are operated under identical conditions so that the inherent variability within the installation can be studied

(4) The periodic determination of moisture-distribution throughout the soil-mass to supplement measures of runoff and seepage

It is hoped that these studies and observations of operation of lysimeters will provide answers to some of the questions raised in the reports of this Committee for 1940 and 1941.

J. KITTREDGE (University of California)--A study entitled "The comparative transpiration-rates of several western conifers" was completed in 1942 by T. W. DANIEL as a Ph.D. thesis at the University of California. He compared the transpiration-rates per unit-area of leaf-surface in a chamber in which a constant temperature of 75°F was maintained for different relative humidities. Ponderosa-pine, Big tree, Port Orford cedar, Monterey pine, and Redwood were in both soil- and water-cultures. As the relative humidities were reduced from 90 through 70 and 50 to 30 per cent the transpiration-rates increased but at a decreasing rate in contrast to the vapor-pressure differences which, of course, increased at a uniform rate. Differences between species and between the water- and soil-cultures for the most part were not large.

My own work during the past year has not included any developments in the analysis of evaporation- or transpiration-data.

C. W. THORNTHWAITE (Soil Conservation Service)--For more than a year our work in evaporation has been directed toward the objective of securing an improved measure of eddy-diffusivity. We had discovered that the familiar logarithmic law of wind-distribution is valid only under certain special conditions, when the temperature lapse-rate is adiabatic or near adiabatic, and that it fails equally under stable and unstable conditions. In a symposium on the climate of the layer of air near the ground at the annual meeting of the Section of Meteorology in 1942 there were two papers that dealt with this subject. One was by KEPPER, BOELTER, and BROOKS and the other by THORNTHWAITE and HALSTEAD. At the annual meeting of the American Geophysical Union in 1943 there were three papers that dealt with this same subject; they were ones by BROOKS, THORNTHWAITE and KASER, and HALSTEAD.

By examining this material one can see that our method of measuring evaporation through observation of gradients of moisture and wind can yield only approximate results until we are able to introduce an expression that relates eddy-diffusivity (the Austausch-coefficient) to wind-structure more exactly than is possible at present. This is our present task.

H. G. WILM (Rocky Mountain Forest and Range Experiment Station)--As briefly discussed in the report for 1942 of this Committee, the Rocky Mountain Station has started a study of soil-moisture relationships as influenced by timber-cutting on 20 five-acre plots arranged in four randomized blocks under mature lodgepole-pine. In 1940, 16 of these plots were cut-over, leaving four plots uncut and four each with merchantable reserve-stands of 0, 2000, 4000, and 6000 board-feet per acre. On all of the plots, trees smaller than 9.6 inches in diameter were left uncut in addition to the desired reserve-stand of merchantable trees. Since treatment, data have been taken on snow-storage and melting-rates, net and gross rainfall, and soil-moisture in spring and autumn.

While these experiments will not be completed for several years, preliminary results are worth summarizing (see Table 1).

Based on one year's data (except for snow-storage, which are averages for two years), timber-cutting has augmented snow-storage and net rainfall, and minimized autumn soil-moisture deficiencies. Under the uncut forest considerable quantities of precipitation were lost by interception (of both snow and rain) and subsequent evaporation from tree-crowns, and the interception of summer rainfall was directly reflected in autumn soil-moisture deficiencies. On these plots, summer rainfall functions mainly to minimize autumn deficiencies, adding little if any water to the ground-water table. Even this service is useful from the water-supply view-point, however, as autumn deficiencies must be replenished by snow-melt before additional melting can provide water for stream-flow.

An interesting point is that while autumn deficiencies, column (8), vary with the density of the reserve stand, total losses of water during the growing season, combining columns (7) and (8), are relatively constant among the various treatments. At least in this one year, if transpiration-rates were diminished by timber-cutting the decrease was apparently offset by increased evaporation.

Table 1--Disposition of precipitation under mature lodgepole-pine, 1941

Reserve-stand, bd-ft per acre	Precipitation reaching the ground				Losses				Water available for stream-flow
	Snow		Rain	To-tal	Snow[b]	Rain[c]	Soil[d]	To-tal	
	Initial	Melt[a]							
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
11,890 (uncut)	5.6	3.5	3.9	13.0	0.8	3.9	1.8	6.5	6.5
6,000	6.9	3.9	4.9	15.7	1.1	4.9	1.5	7.5	8.2
4,000	7.4	4.2	5.2	16.8	1.4	5.2	1.4	8.0	8.8
2,000	7.7	4.6	5.0	17.3	1.7	5.0	1.2	7.9	9.4
0	8.2	5.0	5.5	18.7	2.0	5.5	0.3	7.8	10.9

[a]Approximate precipitation during spring-melt period, derived from climatic-station data. [b]Approximate evaporation from the stored snow. [c]It is assumed that all summer precipitation was lost by evaporation from the soil, as it occurred consistently in small storms (average 0.25 inch) falling on relatively dry soil. [d]Deficiency in soil-moisture at the end of the growing-season (September 15-20).

Several members of the Committee have suggested the following publications as being worth reading:

RUDOLF GEIGER, Das Klima der bodennahen Luftschicht, Die Wissenschaft, v. 78, Braunschweig, Vieweg, 1927.

MAURICE HALSTEAD, A stability term in the wind-gradient equation, Trans. Amer. Geophys. Union, pp. 204-208, 1943.

EMMETT MARTIN, Studies of evaporation and transpiration under controlled conditions, Carnegie Inst. Wash., Pub. 550, 1943.

ADOLPH F. MEYER, Evaporation from lakes and reservoirs, Minn. Resources Comm., 1942.

C. H. NIEDERHOF and H. G. WILM, Effect of cutting mature lodgepole-pine stands on rainfall-interception, J. Forestry, v. 41, pp. 57-61, 1943.

C. W. THORNTHWAITE and BENJAMIN HOLZMAN, Measurement of evaporation from land and water surfaces, U. S. Dep. Agric., Tech. Bull. No. 817, 1942.

A. A. YOUNG, the following three mimeographed reports of the Division of Irrigation, Soil Conservation Service: (1) Evaporation studies at Lake Elsinore, California; (2) Evaporation from covered reservoirs in which ventilation is limited to small screened openings; (3) Investigation of evaporation from a screened pan and development of a coefficient for the conversion of pan evaporation to lake evaporation.

Rocky Mountain Forest and Range Experiment Station,
Fort Collins, Colorado

REPORT OF COMMITTEE ON INFILTRATION, 1942-43

G. W. Musgrave, Chairman

Harry F. Blaney
Howard L. Cook
Gail A. Hathaway
R. A. Hertzler
W. W. Horner
Walter B. Langbein
M. R. Lewis
S. W. Lohman
José Garcia Montes
Byron T. Shaw
L. K. Sherman
Walter N. White
Walter T. Wilson

With the beginning of a new triennium the Committee on Infiltration is reorienting and reorganizing its activities as a means of focusing its attention more directly upon certain phases of the rather broad field of infiltration and in an endeavor to secure the utmost efficiency in its work. Sub-Committees are being organized as follows:

(1) Infiltration and the Physics of Soil-Moisture and of the Infiltration-Process
(2) Infiltration in Relation to Ground-Water
(3) Infiltration in Relation to Snow and Its Physical Properties
(4) Infiltration in Relation to Irrigation and Methods of Irrigation
(5) Infiltration in Relation to Evapo-Transpiration
(6) Infiltration in Relation to Surface-Runoff

This reorganization is in part an outgrowth of a discussion between the Chairman of this Committee and the Chairman of the Committee on Snow, in which the need of closer collaboration was recognized and plans formulated for securing it.

Obviously interrelationships exist between the subject-matter of each of the research-committees of the Section, and it is preferable to recognize rather than to ignore them. The breakdown by subjects as indicated by the titles of the six Sub-Committees, though not complete, is viewed as a start in the right direction and one which possibly gives most promise of progress.

During a wartime period it is fitting that our research-activities should be concerned with wartime problems. During the past year several members of the Committee have been working on problems, the solution of which is important to the war effort. Particularly research basic to the design of drainage-systems for strip-airports should be noted, as well as actual application of findings of research to the same purpose.

One member of the Committee has been conducting studies to determine the amount of soil-moisture available from precipitation for growing Guayule on non-irrigated lands. Infiltration-measurements were made on various soils and land-use conditions, and it is planned during the current year (1943) to conduct some studies on several types of irrigated soils. Mr. BLANEY and his associates have shown the immense possibilities which exist in the more efficient use of irrigation-water.

The subject-matter dealt with in this Section in the past has included mainly the engineering phases of hydrology, relating especially to stream-flow. Is it not true that there are also agricultural phases deserving of more attention than they have received thus far? For example, the layman is inclined to the impression that in humid regions water is available in ample quantities for the use of man as well as of plants. Referring at this time only to plants, the fallacy can be made apparent by a glance at conditions surrounding the record-crop of corn in 1942 in contrast to the conditions obtaining the preceding year. In the leading corn-producing state (Iowa) the average yield per acre (61.5 bushels) exceeded that of the previous year by over 20 per cent. Though the annual precipitation was greater in 1941 than in 1942, the rainfall in 1942 for the period April to August was larger and more evenly distributed, evaporation was less, humidity was higher, and infiltration was greater. The higher yield must be attributed primarily to hydrologic factors since the acreage had expanded somewhat from that of the previous year so as to include less favorable soil, shortages of labor had appeared, and practically all other known factors except climatic and hydrologic ones were less favorable in 1942 than in 1941.

The point which it is desired to make is that hydrology as a science has a contribution to make, the importance of which the public does not appreciate and one that perhaps we ourselves do not fully appreciate at this time. Water is of the utmost value to man and its regulated use is essential. This includes not only protection of the needs of industries and municipalities, but also of agriculture. It calls for more general recognition of the fact that urban needs for ground-water, for example, are largely met from precipitation occurring in agricultural areas, that hydrology is of concern to engineers and agricultural workers alike. In no phase of hydrology is this more

important than in those problems with which this Committee is concerned since in actuality all terrestrial life--both plant and animal--is dependent upon water which infiltrates into the soil.

There is an urgent need for further data as to the effect of infiltration upon irrigation-practices of various types, and the effect of irrigation-water having varying amounts of salinity as well as the relation of both of these factors to various soil-types. Particularly pertinent under the present wartime conditions with its pressure for production of food, is the obvious need of tracing the effect of infiltrated water on crop-yields. There is little doubt that even in humid portions of the country seasonal deficiencies in supplies of moisture occur with considerable frequency. THORNTHWAITE [see 7 of "References" at end of report] shows that the moist sub-humid climate (that is, the normal climate of the crop-season of about the 100th meridian) is found from one-eighth to one-half of the time in the States east of the Mississippi River. Most probably much of the deficiency of soil-moisture thus occasioned might be modified by practices that increase infiltration. Many of these practices are ones which are recognized as being generally desirable in soil-management.

Among the more urgent items of continuing research that is needed are those dealing with problems occurring upon airports. This is a matter which has been emphasized by both Messrs. HATHAWAY and HORNER. The effects of dense turf in protecting the surface of the soil from the impact of rain and the effect of the turf upon the flow-characteristics of surface-water are extremely important. It is good to be able to report that work on this problem has already started and that it is hoped within the next few months to make some very definite progress. The paper by C. F. IZZARD, dealing with studies upon paved surfaces, indicates in a general way the methods which at present are planned for the continuing work on turfed areas [Trans. Amer. Geophys. Union, pp. 500-511, 1943].

Further work in developing the fundamental relationships of the infiltration-process likewise is important. Furthermore, the time is approaching when we should begin the assembly of all existing data on infiltration applicable to various parts of the country. This presents several difficult problems, particularly as to the best methods of presenting such data. Perhaps in its early stages the data may be presented as f_c-values with examples of typical curves showing decline in rate with lapse of time.

In certain areas where munitions plants are dependent upon cool water for the operation of distillation-processes, deficiencies in ground-water have appeared, as pointed out by SUTER during the meeting of 1943 [see pp. 493-500]. The deficiencies have become so critical that the utmost concern is warranted. The extent to which improved infiltration may result in recharge of ground-water under certain of these conditions is not definitely known but preliminary work indicates that marked improvement in the rate of infiltration is thoroughly feasible. At the same time, other work has indicated that infiltration providing only about five inches more water per annum, if transmitted to the ground-water table, would alleviate this particular situation.

Attention may be called to several papers published during the year in other journals and of more than common interest. HORNER and JENS' paper on the determination of surface-runoff from rainfall without using coefficients [3] demonstrates a practical application of the infiltration-concept to a specific engineering problem. A later paper by HORNER, "The role of the land during flood periods" [4], points out still other applications of the same concept. BODMAN's "Nomograms for rapid calculation of soil density, water content, and total porosity" [1], will be found useful by many workers in our field. HASTINGS and DEAN [2], reporting 17 years of lysimeter-data from north central Oregon, show efficient use by alfalfa of large quantities of infiltrated water and relatively small outgo below a six-foot depth of soil; their comparison of evaporation from a free water-surface and from bare soil (the latter averaging 54 per cent of the former) provides a datum of interest. Soil-technologists have made considerable progress also. The method of LEAMER and SHAW [5] for determining pore-sizes in soils seems basically sound and thoroughly applicable and is entering into rather general use. The micrometric method of determining pore-size [6] likewise seems to be basically sound and entirely practicable. As a result of these two developments, it may be expected that evidence on the relations of pore-size to infiltration-rates may be forthcoming in the near future.

These papers, in addition to those published in this volume, clearly indicate that definite progress and some notable contributions have been made during the year. Military service, however, is attracting much of the technical personnel and such progress can scarcely be maintained throughout the war period. There is the opportunity during this period, nevertheless, to plan for post-war activity, a matter obviously of the utmost importance which should not be neglected.

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[3] W. W. HORNER and S. W. JENS, Surface runoff determination from rainfall without using coefficients, Trans. Amer. Soc. Civ. Eng., v. 107, 1942.
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U. S. Department of Agriculture,
Washington, D. C.

REPORT OF COMMITTEE ON PHYSICS OF SOIL-MOISTURE, 1942-43

F. J. Veihmeyer, Chairman

The membership of the Committee is as follows:

Dr. L. D. Baver, North Carolina State College, Raleigh, North Carolina
Dr. G. B. Bodman, University of California, Berkeley, California
Dr. Richard Bradfield, Cornell University, Ithaca, New York
S. J. Buchanan, United States Waterways Experiment Station, Vicksburg, Mississippi
Dr. T. F. Buehrer, University of Arizona, Tucson, Arizona
Dr. I. A. Denison, National Bureau of Standards, United States Department of Commerce, Washington, D. C.
Dr. N. E. Edlefsen, University of California, Davis, California (on leave)
Dr. Willard Gardner, Utah Experiment Station, Logan, Utah
Dr. Glennon Gilboy, Massachusetts Institute of Technology, Cambridge, Massachusetts
Dr. O. W. Israelsen, Utah State Agricultural College, Logan, Utah
Dr. L. B. Olmstead, Bureau of Plant Industry, United States Department of Agriculture, Washington, D. C.
Dr. L. A. Richards, Bureau of Plant Industry, United States Department of Agriculture, Riverside, California
E. A. Willis, Bureau of Public Roads, United States Department of Agriculture, Washington, D. C.
Dr. F. J. Veihmeyer, University of California, Davis, California

The activities of the Committee on Physics of Soil-Moisture have been drastically curtailed because of the national emergency. Dr. N. E. EDLEFSEN, Chairman of the Committee for the period 1940-42, was called to assist in investigations in connection with the war effort, and was compelled to relinquish the chairmanship. Dr. L. D. BAVER was asked to act as Chairman of the Committee, but recently found that he could not undertake the obligation in view of the press of other duties. President CHURCH then drafted F. J. VEIHMEYER to serve as Chairman. The short time available has precluded the possibility of following the usual method of preparing the report of the Committee.

Since 1943 is the tenth anniversary of the organization of the Committee on Physics of Soil-Moisture, it was thought appropriate that the work of the Committee be briefly reported.

The members of the original Committee appointed by President O. E. MEINZER were: F. J. Alway; T. F. Buehrer; J. S. Cole; N. E. Edlefsen; H. J. Fraser; G. E. Ladd; J. C. Russel; W. O. Smith; E. A. Willis; and F. J. Veihmeyer. In the next year, 1934, the following members were added: I. A. Denison; P. G. Nutting; L. B. Olmstead; and O. W. Israelsen, and then L. D. Baver, G. B. Bodman, and R. E. Horton were appointed members of the Committee. Most of these have continued their interest in the work of the Committee and participated in preparing its reports. For the past three years, the Committee has been constituted as indicated at the beginning

of this report. The Chairman of the Committee was F. J. Veihmeyer from 1932 to 1939 and N. E. Edlefsen from 1940 to 1942.

When the Committee was first organized, the following was the statement of its purpose: "This Committee is concerned with the molecular forces that control or influence the occurrence and movement of water in the interstices of the soil and rock-formations, including the dynamics of soil-moisture in landslides, mud-flows, subsidences, and frost-action. The field of the Committee touches that of Absorption and Transpiration and, also to some extent, that of Underground Water. It also touches the field of the Central Petroleum Committee and the Committee on Petroleum Geology of the National Research Council."

The wide geographical distribution of members of the Committee precluded the possibility of meeting as a group. The work then was largely confined to correspondence. The assistance of the members was sought by the Chairman in a discussion of a definite problem, the final report being a compilation of opinions and discussions, not only of members, but others who were active in the particular phases of the soil-moisture problem under discussion. This scheme was followed throughout the ten years the Committee has functioned.

The first report of the Committee resulted in the publication of two papers entitled "Forces acting on soil-moisture in relation to other fundamental functions" by N. E. EDLEFSEN [Trans. Amer. Geophys. Union, pp. 328-330, 1932] and "The disposal of moisture from the aerated portion of soils" by F. J. VEIHMEYER Trans., pp. 330-331, 1932 .

In 1933, a review of the problems under investigations in the field of soil-moisture was discussed by members of the Committee [Trans., pp. 363-365, 1933].

In 1934, the Committee concerned itself with concise statements dealing with the usefulness of soil-moisture functions and constants [Trans., pp. 302-312, 1934]. Members of the Committee and others who were engaged in soil-moisture investigations were asked to give their opinion as to the usefulness of soil-moisture functions and so-called soil-moisture constants with which they had worked.

For the report of 1935, information concerning the total pore-space of soils in place in the field was obtained [Trans., pp. 426-432, 1935]. A questionnaire was sent to at least one investigator in every State and, in some cases, to several, to secure an expression of opinion and data from competent investigators as to the relation between pore-space and texture of soils in place in the field. Wide differences of opinion among contributors on this relationship were obtained. Most of the data indicate that porosity is independent of texture, but generalizations as to the relation of porosity to soil-texture are not justified.

In 1936, the report was made on the physical properties of soils as affected by the degree of cation saturation [Trans., pp. 318-326, 1936]. The Committee solicited information as to the measurements produced by changes in the kinds and proportions of replaceable cations in the absorptive complex. The summaries of the information gathered show that laboratory physical measurements, such as moisture-equivalent, permeability, deflocculation, absorption of water-vapor, heat of wetting, density during drying, hardness of crumbs of the dried soil, and cohesiveness are all increased by the substitution of sodium or potassium ions in the base-exchange complex and are decreased by the substitution of calcium or hydrogen. On the other hand, a lack of definite information concerning the effect of the substitution of various ions in the soils in place in the field was evident.

The report of the Committee for the year 1937 had for its nucleus a paper prepared by F. J. VEIHMEYER and N. E. EDLEFSEN, entitled "Interpretation of soil-moisture problems by means of energy-changes" [Trans., pp. 302-308, 1937], followed by discussions by members of the Committee and a selected list of contributors on the various points raised in the paper.

In 1938, a report entitled "Effect of organic matter on the infiltration of water into soils" was made [Trans., pp. 326-342, 1938]. The problem was broken down into various phases and, following the procedure used in previous reports, discussions were obtained from investigators in the field.

The subject for the report for the year 1939 was the validity of the assumption that it is possible to produce different moisture-percentages in field-soils [Trans., pp. 543-545, 1939]

For the year 1940, the report of the Committee; under Chairman N. E. EDLEFSEN, was a discussion of a paper prepared by L. D. BAVER under the title "Soil-porosity in relation to gaseous and water-movement." The paper produced a lively discussion and questions were raised which should serve to stimulate future research.

The report for 1941 of the Committee which, as in the past, was intended as a symposium on some aspects of the physics of soil-moisture, was a discussion of a paper prepared by the Chairman, N. E. EDLEFSEN, under the title "Some thermodynamic aspects of the use of soil-moisture by plants" [Trans., pp. 917-940, 1941]. Many contributors to the discussion of this report were new to the Transactions of the American Geophysical Union since most of them were plant physiologists. The paper by Dr. Edlefsen was deliberately intended to provoke discussion. He approached the subject of movement of water in plants from basic concepts of thermodynamics and pointed out the ambiguity in some of the reasoning used by investigators in this field, and concluded the discussion by stating: "The language of mathematics and thermodynamics is only a tool and helps in analysis because most of us have not common sense in adequate degree, and neither have we mental ability to carry in our minds the detailed reasoning which is necessary in the analysis of complicated problems such as one finds in connection with the use of soil-moisture by plants as well as other soils and plant-physiological problems. Many, therefore, find the thermodynamic reasoning helpful."

The report of the Committee for 1942 had for its nucleus a paper prepared by ALFRED B. C. ANDERSON, JOEL E. FLETCHER, and N. E. EDLEFSEN, under the title "Soil-moisture conditions and phenomena in frozen soils" [Trans., pp. 355-371, 1942]. As in previous reports, a discussion was prepared by investigators who were interested in this phase of the soil-moisture problem.

A restatement of the purpose of the Committee on Physics of Soil-Moisture by the Sub-Committee on Research-Committees of the Union, published June 30, 1943, is as follows: "The scope of activity of the Committee on the Physics of Soil-Moisture embraces the occurrence and movement of moisture within the soil or rock-mantle. This field includes: Measurement of rates and volumes; the dynamics of soil-moisture; the relation of soil-characteristics to moisture; the effect of vegetal roots on moisture; and related research. The Committee will coordinate its work particularly with that of the research-committees on Infiltration, Ground-water, Runoff, Erosion, Evaporation and Transpiration, and Chemistry of Natural Waters."

University of California,
Davis, California

REPORT OF SUB-COMMITTEE ON LAND FORMS OF COMMITTEE ON DYNAMICS OF STREAMS, 1942-43

Irving B. Crosby, Chairman

The Sub-Committee on Land Forms of the Committee on the Dynamics of Streams has continued its studies, insofar as the abnormal conditions have permitted. All the members have been involved in war activities and most of them have been unable to give any attention to the problems of the Sub-Committee. Progress has been made, however, with the study of the causes and controlling factors of stream-meanders and in the study of entrenched meanders.

In regard to the first, GERARD H. MATTHES reports that: "During the latter part of 1942 tests were started aimed at establishing the function and also the relative importance of each of the primary factors which influence the meandering habits of natural streams flowing unrestrained in alluvial materials of their own deposition. These tests are an extension of those made in 1941 in a bed of granulated coal [see Trans. Amer. Geophys. Union, p. 477, 1941]. The desirability of making observations on streams flowing in natural river sands having been repeatedly stressed, the new test-series were undertaken in sand and silt-mixtures taken from the Mississippi River. Other materials were also used, including haydite. The indications are that the meander-pattern is affected by each of the variables previously determined, namely, valley-slope, grain-size of material, discharge-volume, bed-load, and vegetation. To what degree and under what conditions each of these variables affects the shape of a meandering channel does not appear to have been previously established by experimenters elsewhere. Definite knowledge on this subject appears to have a fundamental bearing on the stabilization of meandering rivers. The purpose of the new tests is intimately connected with the problems arising in the maintenance of the lower Mississippi River. It is planned to continue the test-series into 1943."

The Chairman of the Sub-Committee made observations on entrenched meanders on the Cumberland River in Kentucky. At Burnside, Kentucky, a meander-loop of the Cumberland River which was entrenched 200 feet was cut-off by lateral erosion and subsequent to the cut-off the Cumberland River has deepened its channel 60 to 80 feet. This deepening was only partly due to the cut-off, as is shown by the fact that the South Fork of the Cumberland has also deepened its channel. Other meanders upstream on the Cumberland River and also on the South Fork of the Cumberland River, show different stages in the development of entrenched meanders.

Previously, the Chairman had observed interesting features on the Little Tennessee River in eastern Tennessee. This river has cut its low-water channel into the hard bed-rock floor of the high-water channel. The low-water channel was considerably shorter than the high-water channel, and hugged the inside of the bends. Similar conditions were observed by Mr. MATTHES on an entrenched section of the Tennessee River above Chattanooga, where the gradient of the river has been steepened and the river is tending to straighten the bends. These observations on the Cumberland and Tennessee rivers indicate a few of the problems connected with entrenched meanders which merit further study.

6 Beacon Street,
Boston 8, Massachusetts

REPORT OF COMMITTEE ON GROUND WATER, 1942-43

S. W. Lohman, Chairman

P. I. Aguerrevere	F. H. Lahee	Max Suter
J. Harlan Bretz	A. M. Piper	A. C. Swinnerton
V. C. Fishel	N. A. Rose	C. V. Theis
Willard Gardner	H. T. Stearns	Franklin Thomas
C. S. Howard		L. K. Wenzel

Professor Swinnerton and Dr. Lahee asked to resign from the Committee at least for the duration of the war but they have been persuaded to remain on the Committee in the hope that after the war they can again take active part.

The recent untimely deaths of DAVID G. THOMPSON and Major RICHARD C. CADY came as a severe shock to their many friends and fellow-workers in ground-water hydrology. Fitting memorials to these men by O. E. MEINZER are presented in these Transactions [pp. 9-12], and the Committee also wishes to pay sincere tribute to these two distinguished ground-water geologists. As Chairman of the Committee on Ground Water for many years, Mr. Thompson gave unstintingly of his time and energy, and in taking over this responsibility the present Chairman realizes with a deep sense of humility the difficulties of maintaining the excellent standard he established.

President CHURCH has expressed a desire to expand the activities of the Section of Hydrology to embrace all of the Americas. It is hoped that the Committee on Ground Water may participate in these activities through its member in Venezuela, Señor P. I. AGUERREVERE.

The present Chairman and other members of this Committee were appointed in the spring of 1943, hence it has not yet been possible to hear from all members and other workers that have been solicited. Moreover, most of the ground-water hydrologists contacted are busily engaged on problems relating directly to the war. It is mainly for these reasons that this report is not as comprehensive as those of former years, and that no attempt is being made to incorporate a list of current publications in the field of ground-water hydrology. Attention is called, however, to the outstanding publication of the year, "Hydrology," which was edited by Dr. O. E. MEINZER and was published in 1942 by the McGraw-Hill Book Company as volume IX in the Physics-of-the-Earth Series. This volume contains contributions by foremost workers in the several branches of the science of hydrology.

The opinions of members of the Committee and others have been requested regarding the advisability of following the lead of several of the other Research-Committees in selecting each year for discussion one or more controversial subjects in the field of ground water. After selection of a suitable subject by the Committee, a person or persons well qualified in the particular subject would be asked to prepare a paper for ultimate publication in the Transactions. Prior to presentation, the paper would be reviewed by one or more qualified persons, and the discussion

and author's rebuttal would be published with the papers. Excellent suggestions for such topics have been received from several members and are given below. It is hoped that other members will be heard from and that one or more topics can be selected for inclusion in the Transactions of 1944.

M. K. HUBBERT suggested to L. K. WENZEL and the Chairman the advisability of appointing a Sub-Committee on Permeability, the purpose of which is well stated by Dr. Hubbert as follows:

"There appears to be a growing feeling among those interested in the theory of ground-water flow that the problem now most urgently needing attention is that of proper units of measurement. A number of people at the meeting seemed to think that a great deal could be accomplished if this problem could be aired out over the next several years, without any idea of official action being taken in the direction of formalizing any particular system of units. It was felt that the problem is in a high state of confusion at the present time, and that as soon as that confusion can be replaced by a genuine understanding, the solution in the form of the agreement upon suitable units of measurement will occur automatically, but that any official action toward adopting any system of units prior to that time would be premature."

Acting on Dr. Hubbert's excellent and timely suggestion, the following have been appointed members of this Sub-Committee, with the approval of President CHURCH: V. C. Fishel; L. P. Hatch; M. K. Hubbert; O. W. Israelson; C. E. Jacob; O. E. Meinzer; Morris Muskat; L. A. Richards; C. V. Theis; and L. K. Wenzel (Chairman). It is hoped that this Sub-Committee will be able to report at least tentative conclusions of its findings at the meeting in 1944.

The following statements have been received from members of the Committee on Ground Water and others:

O. E. MEINZER has submitted excellent reports on (1) "The work of the International Commission on Subterranean Water in the Western Hemisphere," of which he is President, and (2) "The work of the Geological Survey and cooperating State agencies on ground water for war purposes," which form Appendices A and B to this report.

N. A. ROSE (U. S. Geological Survey, Houston, Texas) has submitted a comprehensive "Report on research in the field of ground water being conducted by oil companies," which forms Appendix C to this report. Because of the temporary resignation of Dr. F. H. LAHEE from the Committee it was not practicable for him to submit his usual report on this subject, but he has collaborated with Mr. Rose in the preparation of the present report.

A. C. SWINNERTON is now doing important war work with the Research and Development Division of the Signal Corps, hence has been unable to submit his usual statement on current research on the hydrology and physiography of limestone terranes. Professor Swinnerton states, however, that "The notable contribution to limestone physiography and hydrology during the year was unquestionably J. HARLEN BRETZ's 'Vadose and phreatic features of limestone caverns' [J. Geol., v. 50, pp. 675-811, 1942]."

Dr. Bretz was asked to submit a statement regarding current research in this field, but feels that he is not sufficiently acquainted with the ground-water aspects of the problem. He also stated that: "My limestone-cave paper was definitely on a controversial subject and was equally definitely on one side. When some proponent of the opposite view answers it with an adequate array of field-evidence or counters my arguments as built on my evidence, the Section of Hydrology might perhaps stage a symposium in its program on the question of vadose versus phreatic origin of limestone caves."

The origin of limestone caverns has long been a controversy and it is hoped that eventually a symposium on the subject may be staged as suggested by Dr. Bretz.

WILLARD GARDNER (Utah State Agricultural College, Logan, Utah) has submitted the following statement regarding current research by him and his associates:

"SAMUEL W. HARDING and JOHN K. WOOD, two of our graduate students, published a short paper [Proc. Soil Sci. Soc. Amer., v. 6, 1941] entitled 'Model tests of flow into drains.' Previous to this Dr. DON KIRKHAM had published a series of papers along the same line. Since that time we have been devoting our attention to soil-erosion, with particular reference to irrigation.

"Dr. O. W. ISRAELSEN and Dr. C. W. LAURITZEN, also working in connection with the Soil Conservation Service, are making some studies regarding loss of water by seepage from canals, and I believe they are obtaining some interesting data. JERALD CHRISTIANSEN, at the United States Salinity Laboratories, Riverside, California, is obtaining some good results in drainage-design.

"In our laboratory we are more particularly interested at the present time in the dynamics of erosion. We are trying to find a semi-empirical formula to express the silt-content of the eroding water as a function of the distance from the intake, and the time, the size of the stream, the slope of the ground, and the soil-characteristics entering as parameters. We hope to combine this equation with the equation of continuity for the silt to obtain information of fundamental character. Our experimental study is progressing satisfactorily but it is too early to say very much about the outcome as yet. Our work has been confined to laboratory flumes thus far and to one type of soil.

"I do not agree with the point of view of some of our men in soil-physics who have discussed the soil-moisture problem recently; I have in mind in particular the Buckingham capillary potential and its significance in the dynamics of soil-moisture. SCHOFIELD suggested taking its logarithm and calling it the pF, but the pF does not enter into the dynamics except in what seems to me to be a rather clumsy manner. I would like to see Dr. L. A. RICHARDS and Dr. L. D. BAVER discuss the problem. This may be a little remote from the standpoint of ground water, but I believe there should be more constructive criticism in the literature."

The Chairman believes it would be very worth while to follow up the suggestion in the last paragraph of Dr. Gardner's letter, and has suggested to him that he take up the matter with Dr. F. J. VEIHMEYER for appropriate action by his Committee on the Physics of Soil-Moisture.

MAX SUTER (Illinois State Water Survey Division) and G. W. MUSGRAVE (Soil Conservation Service) have written regarding the intensive water-supply investigation in the Peoria Area of Illinois, which is being participated in by the following agencies: National Resources Planning Board; United States Engineers; United States Geological Survey; Illinois Geological Survey; Illinois Agricultural Experiment Station; Peoria Association of Commerce; Illinois State Water Survey Division; and the Soil Conservation Service. Dr. Suter's paper on "A pilot study of ground-water resources in Peoria County, Illinois" published in these Transactions [pp. 493-500] describes this study in detail, and Mr. Musgrave has submitted the following additional comments:

"In connection with MAX SUTER's study of ground-water depletion in the Peoria Area, where there are some definite relationships with the successful operation of wartime industries, we have been participating largely in studies of the surface-condition of the land believed to be contributory to the wells in question. We made some rather extensive infiltration-studies in the area last year and on my recent trip to Illinois we developed plans for some expansion of the work this year.

"In addition to our studies of infiltration on different soil-types and under different land-use conditions, we plan to obtain data on the periodic change in moisture-gradient through the surface six feet of soil, and it is also possible that we shall establish under measurement a few small watersheds upon which the different soils and land-use conditions are separately represented, and where rainfall and runoff will be determined as well as where infiltrometer-measurements will be inaugurated in a manner to permit direct comparison with the data of the watershed.

"Dr. Suter of course is developing his ground-water studies and we have loaned from the Soil Conservation Service some water-stage recorders as well as some recording rain-gages.

"Some time ago I wrote to Dr. Suter and Dr. Buswell to see whether or not one of them would care to present a paper on the problem for the spring meeting of the American Geophysical Union. Dr. Suter has been designated to do so and I saw a part of his manuscript while at Urbana. This manuscript will probably not go into detail on the preliminary data but more likely will cover the over-all plan of study more fully than I have indicated in this letter. I might say that the plan in brief encompasses studies not only at the ground-surface but at several succeeding depths, giving particular attention to the soil-characteristics to a depth of 20 feet, and, of course, to the geologic formations as well as the further development of the ground-water profile.

"I have myself been very much interested in this particular problem for several reasons. One of these is that it appears we may be permitted, through joint cooperation with many agencies, to carry forward a fairly broad attack upon the problem. Another reason is that my own interests in infiltration have never before been tied in very concretely to ground-water problems. Still other reasons include the very great importance of the situation where war industries are quite likely dependent upon some fairly definite improvement in the near future, where land-usage is apparently an important factor and where Soil Conservation Districts already present in the area provide a feasible mechanism to achieve any desired changes."

C. V. THEIS (in charge of ground-water investigations in New Mexico by the Federal Geological Survey) has submitted the following statement:

"The extra Army work and reduced personnel have prevented this office from doing any fundamental research during the past year. I have a few data which I hope to amplify when time permits on the nature of draw-down in limestone wells. Although I will need more information before publication there is very little doubt in my mind that in certain types of limestone aquifers Darcy's

law does not hold in the vicinity of the pumped well and that the production of these wells is approximately proportional to the two-thirds power of the draw-down. The flow in these aquifers in the vicinity of the well apparently approximates the flow in very rough pipes.

"It seems to me that it is likely to be very difficult to work up a good symposium on ground water during the war because of the shortage of available men and of time of those men who are available. Whatever subject is selected should, I think, be related to the war. A symposium on the hydraulics of ground water might come in this category. Such a symposium should attempt to bring together the new ideas on this subject and evaluate conflicting opinions. If the symposium could result in a somewhat unified presentation of the methods available for estimating ground-water supplies it might be quite useful for military and allied purposes."

From the experience had in dealing with many war problems here in Kansas, the Chairman feels that the symposium suggested by Dr. Theis is very timely and essential, and it is hoped that his suggestion can be carried out.

A. M. PIPER (in charge of ground-water investigations on the Pacific Coast by the Federal Geological Survey) has submitted the following statement of current ground-water investigations being made under his supervision by the Geological Survey and its cooperating agencies, and has included several timely subjects for attention by the Committee on Ground Water:

"Investigation of ground-water conditions are being made currently under the direction of this office in four general areas along the Pacific Coast. These areas and the general conditions of ground-water occurrence are described briefly beyond.

"In the vicinity of Tacoma and Spokane, Washington, investigations are being made to estimate the potential perennial yield of deposits of glacial origin; the two areas differ greatly in the character and continuity of water-bearing zones, in the facilities for replenishment, and in potential yield. In both areas there are extensive plains formed by the deposits of former melt-water streams. At Tacoma, the outwash plains are underlain by extremely heterogeneous materials whose water-yielding capacity ranges greatly from place to place. For example, one municipal well in South Tacoma has a yield of about 7,500 gallons a minute but another well of equal depth and only about 500 feet away was abandoned because its tested capacity was only about 100 gallons a minute. Large yields of water can be obtained only from wells which tap tongues of gravel that fill valleys on a former land-surface. In contrast, the greater part of the Spokane Valley is underlain by material which is relatively uniform in permeability. Dug wells that penetrate only a few feet below the water-table have yields of several hundred to several thousand gallons a minute. In the valley as a whole, the underflow is estimated to be not less than 1,000 second-feet on the average.

"In the area of the Columbia Basin Irrigation Project of central Washington, the occurrence of ground water is being investigated with respect to the availability of water for domestic use by settlers, to the availability for supplemental irrigation on outlying lands, to the possibility that future extensive irrigation will create drainage-problems, also with respect to certain features in the design of irrigation-works. Thus far, a general reconnaissance has been extended over all the area. More intensive study will now be undertaken and carried on progressively in the order of but in advance of the opening of the lands to settlement.

"In the Long Beach-Santa Ana Area of southern California, the character of the so-called coastal barrier is being studied with respect to its effectiveness as a barrier against salt-water invasion. In this area, bodies of confined ground water have been somewhat overdrawn so that the head is below sea-level across two-thirds the width of the coastal plain and pumping levels within two miles of the coast have been as low as 80 feet below sea-level. Under these conditions, salty water has been drawn from wells at several places along the coast. Thus far, the investigation indicates that this contamination may come from the ocean, from oil-well brines, or industrial wastes; as yet, the source or sources of contamination for specific places have not been discriminated.

"In Santa Barbara County, California, a county-wide inventory of all water-resources is being carried on. The water-supply of this county must be derived substantially all from rain that falls within its own area--none of the streams in the county drain extensive outlying areas. The potential residential and agricultural development of the county probably will be limited by the magnitude of the perennial water-supply, including water diverted from or impounded along the streams, together with water drawn from beneath the land-surface. Factual data being gathered by the Geological Survey in this inventory are being applied by other Federal agencies to the design of dams and the planning of water-utilization programs.

"Like other field-offices of the Ground-Water Division, this office has, in a number of areas, appraised the availability of ground-water supplies for military establishments and other war activities. In considerable part, such appraisals must be made in areas that heretofore have not been thoroughly explored, so that a judgment must be made on the basis of few factual data. In contrast, in other areas military necessity calls for establishment in an area whose water-supply

already is fully developed or possibly somewhat overdeveloped. In such areas, the only recourse is to accede in some further overdraft but to guide the future development so as to minimize the interference with antecedent water-supply developments.

"With respect to your suggestion that the Committee on Ground Water select some controversial subject or subjects for comprehensive discussion, may I suggest four general subjects as follows: (1) The interpretation of chemical analyses of ground waters with respect to source and movement of the water and to changes in chemical character within an area; graphic and other methods of study might be considered. (2) Techniques for exploring ground-water conditions by electrical methods, including 'electrical logs,' determinations of specific conductance in wells, and estimates of velocity in wells; heretofore, work in this field has been largely qualitative, however, it is felt that much more effective and specific techniques can be developed. (3) A general appraisal of the interplay and relationships between rainfall, runoff, and fluctuations in ground-water storage; in recent years, there have been numerous papers dealing with some aspect or aspects of the relation between rainfall and runoff but few of these appear to involve an adequate concept of the related ground-water conditions; this field of investigation may develop into an effective line of attack on certain types of ground-water problems and, accordingly, it seems desirable at this time that it be placed on a completely sound and thoroughly logical basis. (4) Review of the methods for quantitative ground-water estimates with respect to the applicability of mathematical treatments such as those developed by THEIS, JACOB, and others; with respect to evaluating field-conditions in comparison with the ideal conditions that have been analyzed mathematically; and with respect to the need for new field-techniques or new field-instruments."

Mr. Piper's suggested topics, the last of which is very similar to that suggested by Dr. Theis, are all very worthy of attention, and it is hoped that one or more of these can be presented and discussed at the next meeting.

L. K. WENZEL (U. S. Geological Survey, Washington, D. C.) has submitted the following statement regarding a subject for investigation by the Committee, and, as Chairman of the Committee on Observation Wells of the Geological Survey, has submitted a description of the Survey's nation-wide network of observation-wells.

"It may be of interest to note that pumping tests to determine the hydrologic properties of aquifers are being used more and more, and that the use of these methods has resulted in many successful quantitative determinations of ground-water supplies for war activities that would have otherwise not been possible. A suggested subject for investigation by the Committee is that pertaining to 'subsurface storm-runoff.' As you know, this term is now being used rather widely but to many ground-water hydrologists, subsurface storm-runoff implies new laws of ground-water flow and other anomalous conditions. If this subject is taken up some time in the future it would, of course, be necessary to include men who are fundamentally interested in surface-runoff as well as those interested in ground water. The whole question appears to be in a state of confusion in so far as I am concerned, although many hydraulic engineers appear to take the attitude that the theory is sound. It is my understanding that some hydrologists have reached the conclusion that, for the present, the best way to dispose of the problem is to distinguish between only two kinds of runoff--that which reaches the stream quickly and that which reaches the stream slowly. Although the whole subject will undoubtedly be of great interest to many engineers interested in surface-runoff, it is questionable just how appropriate it is for our Committee to take up this work. Perhaps such work could be taken up jointly between the Committee on Ground Water and the Committee on Runoff, of which Mr. HOYT is Chairman.

"During 1942 a start was made on a program for reporting each month on current ground-water conditions in the United States. About 125 key observation-wells were selected to form the nucleus of a nation-wide network. Most of the wells selected have been measured periodically in connection with cooperative investigations of the Geological Survey, United States Department of the Interior, in cooperation with Federal, State, and local agencies; a few of the wells were established specifically for the project. Records of water-levels in the key wells at the end of each month are sent to the Washington office of the Geological Survey where general areal conditions shown by the water-level data are correlated and interpreted. The information on ground water is published monthly in the Water Resources Review which contains also data on stream-flow, including floods, in the United States and Canada. Copies of the monthly review can be obtained by writing the Geological Survey, United States Department of the Interior, Washington, D. C."

M. K. HUBBERT (Washington, D. C.) has submitted the following statement regarding a paper he has in preparation.

"I have a theoretical paper in preparation for the Petroleum Division of the American Institute of Mining and Metallurgical Engineers, which is going somewhat more deeply into the basic physical theory of fluid flow through permeable materials than I was able to do in the earlier paper 'Theory of ground-water motion,' published in the Journal of Geology. With the pressure of

war work, however, this manuscript has been put on the shelf and I have not so far been able to complete it. The content of this paper is not significant in terms of the presentation of material that is new in the sense of differing from the conclusions drawn in the earlier paper, but in giving a more rigorous development of certain fundamental points."

CARROLL F. MERRIAM (Pennsylvania Water and Power Company, Baltimore, Maryland) is continuing and extending his interesting studies of the fluctuations of the water-table in the Susquehanna River Basin in Pennsylvania and New York and their relation to the flow of Susquehanna River--a study in which I have been particularly interested ever since I established the observation-wells in Pennsylvania in 1931. In a recent letter Mr. Merriam stated:

"In the paper last year [Trans. Amer. Geophys. Union, pp. 598-603, 1942] I treated the subject only as far as the determination of the index-value and the efforts to hold this value fixed so that a given figure in one year would mean the same as in some other year. If this is not done, the application of this index is going to be greatly limited to relative changes and effort spent in establishing correlations to other things will be largely lost by depending upon a shifting standard.

"Having done all possible within practical limits in this respect, I sought to verify by independent means a curve showing the relation between ground-water level and the low-flow portion of the hydrograph which Dr. HORTON had sent me based upon relatively few years of observation. I was greatly surprised to find how nearly the curve that I derived did agree with Dr. Horton, who did not have the advantage of the longer record and the more carefully refined data.

"Another interesting observation is that the ground water appears to behave as though it were the elevation of a lake having an area of about 300 square miles and provided with a notched outlet so that the rate of outflow is a function of the elevation. Consequently, if not recharged by additional rainfall the decreasing rate of discharge can be predicted for weeks in advance. This might be called the assured flow of the stream, or that flow which could be depended upon regardless of future rainfall.

"It happens that in the Susquehanna this small increment is of great economic importance even though the actual volume of water is particularly small in comparison with the total average annual flow. If only a small amount of water can be depended upon it makes a great deal of difference in the amount of steam capacity that must be available. Consequently, last year this assurance was a factor in permitting thorough overhaul of steam equipment in order to take advantage of this opportunity to get it in best condition to meet the demands of war industries at a later date.

"Up to this time it has been necessary in scheduling repairs and in reporting available capacity to the Federal authorities, to assume that the flow may fall any month to the minimum recorded in 50 years. Now by means of the ground-water index it is possible to foresee the earliest date when such a contingency might occur and thus estimate in advance the length of time when steam units could be safely kept out for repairs.

"It would be well to emphasize that if the Geological Survey had not had the foresight eleven years ago to have started observations this would not have been possible. It took ten years to make sure that the data were reliable and that the relationships derived from them would stand the test of comparing day by day the actual hydrographs with the predictions that might have been made during that time.

"In situations where there are many wells closely located in the same aquifer there is little need of going into the refinement of developing such an index, but in the Susquehanna River Basin there is certainly no continuity in the water-bearing layers.

"We have recently made a recheck of the rating-curves for all the wells and find that only minor alterations are advisable in cases where we had previously only preliminary curves based upon relatively few observations. Otherwise the points during the last year fall as satisfactorily as can be expected on the old curves. A recomputation of the index for 1942 using the revised rating-curves and weighting the wells more in accordance with the confidence that we now have in them after replotting the rating-curves, showed relatively small change in the final figures as compared with those previously derived."

Replies from men in charge of most of the 25 field-offices of the Division of Ground Water of the Federal Geological Survey indicate that in the main regular areal investigations and special research-projects have been curtailed or deferred in favor of all-out assistance in the development of ground-water supplies for war bases and industries, and this is certainly true here in Kansas where our efforts are being directed wholly on problems and areas directly related to the war. The magnitude and nature of the assistance rendered throughout the country and abroad is described by Dr. MEINZER in Appendix B to this report. This subject is treated also in replies quoted above from Messrs. THEIS and PIPER and in some of the replies quoted below.

M. L. BRASHEARS (in charge of ground-water investigations in New York and New England by the Federal Geological Survey) reports on this subject as follows:

"A large amount of ground-water investigational work pertaining to the war effort has been done by the personnel of this office during the year. War work has been done in New York, Pennsylvania, and most of the New England States and has ranged in scope from general inquiries to quantitative studies involving elaborate pumping tests of six to eight weeks' duration. The investigations have been carried out for the War Production Board, the armed forces, and for industrialists engaged in the production of war goods. The studies fall roughly into three types of work: (1) Reconnaissance-surveys to indicate in general the geologic and hydrologic conditions, and to indicate in general the availability of water from public water-supply and ground-water sources; (2) investigations along the sea-coast at places where the encroachment of sea-water is a possibility; (3) quantitative studies for particular areas from which definite quantities of water must be developed. The many reports made as a result of the war work are in manuscript form and have been placed in the confidential files."

Mr. Brashears also reports that observation-well programs in New York and New England are being continued and enlarged, that a study of the mutual interference of artesian wells in the Jameco gravel is nearing completion, that the study of variations in the temperature and chloride-content of ground water in Long Island has been continued, and that studies of the relation of ground-water levels and precipitation on Long Island are being made [see paper by C. E. JACOB, in this volume, pp. 564-573]. Concerning the continuing studies on the temperature and chloride-content of ground waters, Mr. Brashears adds:

"Periodic observations of temperature and determinations of the chloride-content are made at about 350 wells. A recording soil-thermograph station is operated in connection with the temperature-studies. The temperature of the ground water in the vicinity of recharge-wells that return warm water to the ground continued to remain high but no additional lateral spread of noticeable rises were observed. Several large recharge-well developments have been made on Long Island for air-conditioning large war factories. It is perhaps of interest to note that at one of the factories more than 6,500 gallons per minute of warm water is returned to the ground during the summer. An additional development of 2,000 gallons per minute is contemplated. The period for which records are available is short but a general rise of ground-water temperature is indicated. My paper entitled 'Ground-water temperature on Long Island, New York, as affected by recharge of warm water,' was published in volume 36 of Economic Geology in December, 1941. The chloride-content of the ground-water in parts of Brooklyn, where overdevelopment has drawn the water-level considerably below sea-level, continued to rise at a fairly rapid rate--endangering the potability of the ground water in a considerable area. A Water-Supply paper giving the results of the chloride-content studies is in the first stages of preparation. The study of the variation of the chloride-content of the ground water at New Haven, Connecticut, was continued. Periodic collection of samples is made at about 20 wells. Several industrial wells are now pumping water containing more than 3,000 parts per million. Although there was little or no net change in the chloride-content at most of the wells during the year, a general rise of salinity has occurred since 1939."

T. W. ROBINSON (in charge of ground-water investigations in Iowa and South Dakota by the Federal Geological Survey) reports that in addition to the development of water-supplies for war purposes, observation-well programs in the two States are being continued and expanded to include records of water-level and pumpage at certain cities and at one military camp in Iowa. In addition, in Iowa, many field pumping-tests on wells were made, preparation was begun of new subsurface contour- and isopach-maps of key formations and of a map showing areal changes in the quality of water from the Jordan sandstone.

Studies of salt-water intrusion are being continued at many places along the Atlantic and Gulf coastal plains, as described below by Mr. STRINGFIELD, and also are being actively continued in New Jersey by H. C. BARKSDALE and in Virginia by D. J. CEDERSTROM, the men in charge of ground-water investigations in those States by the Federal Geological Survey and its cooperating State agencies. Concerning studies of salt-water intrusion and other problems, V. T. STRINGFIELD (in general charge of cooperative ground-water investigations in the southeastern States for the Federal Geological Survey) reports:

"In Georgia, Mr. WARREN has continued his quantitative studies and the problem of salt-water encroachment in the Coastal Plain. He has made good progress with the pumping tests and other tests to determine the water-bearing capacity of the principal artesian formations which are the source of water for the large industrial supplies as in Savannah and Brunswick. He has mapped the piezometric surface of the principal artesian formations in a large part of southern Georgia, and has obtained much needed information concerning the area of recharge and discharge and movement of the artesian water. In the first part of this calendar year ground-water studies were started in the Piedmont Area of Georgia.

"In Florida, Mr. COOPER has completed some pumping tests in the northeast part of the State to determine the capacity of the principal artesian formations. All of the men in the southeastern States have been loaded with work on military projects. One of the most unique of these was a job by Mr. Cooper for the United States Maritime Commission to determine the quantity of ground water that would have to be pumped from an area to keep it unwatered.

"In southeastern Florida, Mr. BROWN and others continued the quantitative studies and the investigation of the problem of salt-water encroachment. The work of G. G. PARKER has thrown much light on the hydrology of the Everglades. A manuscript on the artesian water in Florida west of the Swanee River by F. C. WESTENDICK and me was completed. This report was prepared at the request of the State Geologist as a companion paper to Water-Supply Paper 773-C. On that job a reconnaissance-map of the piezometric surface of the principal artesian formations in Florida was completed. That map, together with Mr. Warren's map of southern Georgia, covers one of the largest areas in the country in which the piezometric surface for one continuous water-bearing unit has been mapped.

"In Alabama, Mr. CARLSTON completed his areal report on the ground-water resources of the Cretaceous Area of that State, and began an investigation in the Mobile Area, along with his work on military projects. He has obtained much information on the occurrence of water with relatively high fluoride-content, and has prepared a paper on that subject. He has also obtained information on the occurrence of the salt water which may contaminate the fresh ground-water supplies.

"Mr. BROWN, in Mississippi, and Mr. MAHER, in Louisiana, have been especially busy on military projects. In that vital work they have found that electric logs are very helpful. In one critical area it appears that an adequate water-supply would not have been obtained without the use of electric logs. We have need for electric logs in other parts of the Coastal Plain east of the State of Mississippi. However, in view of the fact that the nearest field-office for such service is in Louisiana, only one water-well in South Carolina and a few test-wells for oil have been explored in Alabama, Georgia, Florida, and South Carolina. Messrs. Maher and Brown have given considerable attention to the interpretation and use of electric logs on water-wells.

"Throughout the Coastal Plain of the southeastern States, additional data are gradually being collected, which will give much needed information concerning the occurrence and source of water with relatively high fluoride- and chloride-content and the natural softening of the ground water."

The work for the United States Maritime Commission in Florida was of a rather unusual character, as brought out in the following description by H. H. COOPER, of the Federal Survey:

"The investigation for the United States Maritime Commission was for the purpose of determining the feasibility of constructing and operating three 'wet basins' on Hookers Point, a peninsula about 1,600 feet wide and 3,000 feet long on Tampa Bay, near Tampa, Florida. Basins 75 feet wide, 1,200 feet long, and 100 feet apart were to be excavated to a depth of 17 feet below mean low-water in Tampa Bay, and these basins were to be used for the construction of concrete vessels below sea-level so that launching might be accomplished by opening the gates to the basins and allowing water to flow in around the vessels.

"An estimate was required as to the quantity of water that would have to be pumped from the formation underlying the basins in order to keep them dewatered. In the latter part of April and the first part of May, 1942, 27 wells were drilled on Hookers Point primarily for use in making pumping tests. It was found that a formation having a transmissibility in the order of 15,000 occurred at a depth of 26 feet and more below sea-level but that all formations down to the 26-foot level were rather impervious. Using a transmissibility of 15,000 it was estimated that the maximum necessary pumpage to be expected probably would be about 3,000 gallons a minute but that the necessary pumpage probably would be considerably less than this.

"On a visit to Hookers Point on November 6, 1942, after excavation of the three basins was essentially complete, I estimated that the total pumpage from formations underlying the three basins was slightly less than 1,000 gallons a minute, and I was told that during heavy rains about twice as much water was pumped."

F. H. KLAER, Jr. (in charge of ground-water studies in Ohio by the Federal Geological Survey) reports that detailed quantitative ground-water studies are in progress in the Mill Creek Valley involving the ultimate safe yield of a large well-field and the possible future effect of this pumping on near-by farm wells and on the industrial and municipal wells of the city of Hamilton. Mr. Klaer and R. G. KAZMANN have been making detailed investigations of the character and amount of recharge to wells from a near-by river at the Indiana Ordnance Works at Charleston, Indiana, and, with R. M. JEFFORDS, are making a similar study at Point Pleasant, West Virginia. Mr. Kazmann reports that in areas where a water-bearing formation is recharged by a river he has been successful, from studies of ground-water temperatures, in working out a method for determining the proportion of the well-discharge that is derived from the river. He has also been studying the effects of seasonal ground-water temperatures on the yields and draw-downs of wells, and adds:

"There is a possibility that temperature-differences at various elevations in a water-bearing formation may throw light on different velocities of ground water which are due to differences in permeability of the formation. The surface of these problems has not been scratched and specialized equipment for such temperature-studies is not yet available. At the present time, the Reading office has two maximum-minimum thermometers at its disposal, which can be lowered into a six-inch observation-well to obtain temperatures at various depths. Although the instruments are crude, the temperature-logs obtained have been significant. There is now on order an electrical-resistance thermometer, built to our general specifications, with 150 feet of cable which will enable us to obtain speedy and accurate temperature-logs in observation-wells 1-1/2 inches in diameter or larger. With the aid of this device we will be able to make areal temperature-investigations in somewhat the same manner as we now make water-level observations."

It is hoped that Mr. Kazmann will publish an account of these methods in the near future, for they should prove exceedingly worthwhile.

P. E. DENNIS (in charge of ground-water studies in Utah by the Federal Geological Survey) reports that water-supply problems for war bases and industries has occupied about half the time of his staff, and that in addition general ground-water studies are being carried on in the Escalante Valley, the Flowell Artesian Basin in Millard County, and near the city of Ogden.

S. F. TURNER (in charge of ground-water studies in Arizona by the Federal Geological Survey) reports that pending final arrangements he is preparing to intensify a detailed ground-water investigation now in progress [see Trans. Amer. Geophys. Union, pp. 739-744, 1941] in the Safford Valley of the Gila River at the request of the Defense Plants Corporation and the Phelps-Dodge Corporation, in order to determine the extent to which non-beneficial consumptive uses of water (largely transpiration) will be reduced by elimination of vegetation within the flood-channel of Gila River. In addition, data will be obtained regarding the effect of the removal of vegetation upon the regimen of the river and upon the quality of the water that enters San Carlos Reservoir.

H. A. WAITE (in charge of ground-water studies in Nebraska by the Federal and State Geological Surveys) has been revitalizing the observation-well program, completing areal studies in the Republican Valley, making special studies for several cities, war bases, and one State institution, and is cooperating with the Surface-Water Division in a study along South Platte River involving stream-loss and ground-water "pick up" between Paxton and North Platte.

E. W. REED (in charge of ground-water studies in Oklahoma by the State and Federal Geological Surveys) is engaged in a detailed investigation of the artesian water-supply of the Garber sandstone in Oklahoma and Cleveland counties. The Garber supplies water to several cities and war bases along a narrow belt west of the outcrop, and its study at this time is required in connection with the growing needs of several war bases and cities. The complex geology of the Garber is being studied by MALCOM OAKES of the State Survey and C. L. JACOBSEN of the Federal Survey.

In Kansas, ground-water investigations by the State and Federal Geological Surveys and cooperating agencies are almost wholly connected with the war program except for completion of certain areal studies in western Kansas. Quantitative studies of three important industrial and military areas were begun recently, namely: The Kansas City Area, by V. C. FISHEL; the Salina-Fort Riley Area, by B. F. LATTA; and the lower Arkansas Valley, by C. C. WILLIAMS. Mr. Fishel hopes to obtain considerable information regarding ground-water temperatures in connection with his inventory of the Kansas City Area in order to determine what proportion of the ground-water withdrawal is recharged from the river. It is hoped that he will have an opportunity to try some of the methods being used by Mr. Kazman, as noted above. A detailed quantitative study of the safe yield of the Wichita well-field area by C. C. Williams and others is nearing completion. This study is of special interest in that all significant ground-water conditions in the well-field area were known prior to the beginning of pumping in September, 1940, so that it has been possible to compare detailed water-table contour-maps, prepared quarterly since pumping began, with one another and with a contour-map showing original conditions prior to pumping. By superimposing each contour-map in turn on the original, maps showing lines of equal rise or decline in water-level have been prepared which in turn allow the computation of quarterly changes in ground-water storage over a wide area. These data together with accurate records of pumpage, precipitation, and water-levels provide a fairly complete quantitative picture of this large ground-water development. Among other things this investigation has again emphasized to me the importance of basing quantitative estimates in alluvial areas recharged solely by local precipitation upon ground-water storage and recharge-facilities rather than upon underflow which, as in the Wichita Area, may be rather insignificant as compared to the rate of withdrawal.

U. S. Geological Survey,
Lawrence, Kansas

APPENDIX A--THE WORK OF THE INTERNATIONAL COMMISSION ON SUBTERRANEAN WATER IN THE WESTERN HEMISPHERE

(Contribution for the 1943 annual report of the Committee on Ground Water in the Section of Hydrology, American Geophysical Union)

O. E. Meinzer, President of the Commission

When the International Commission on Subterranean Water was reorganized in 1936 on a world-wide basis, the special importance of the development of ground water and ground-water hydrology in the Latin American countries was recognized. Accordingly, Dr. A. N. SAYRE, of the United States Geological Survey, was appointed to serve on the Commission in the special capacity of Secretary to the Latin American countries. Through the aid of the Pan-American Union, representatives were appointed on the Commission by 14 countries in the Western Hemisphere, including the United States and Canada. Seven of these countries were members of the International Union and are therefore represented on the Commission by full members; the other seven countries did not yet adhere to the International Union and are therefore represented by advisory members.

Although the work of the Commission has been nearly stopped in the Eastern Hemisphere on account of the war, contact has been maintained with the members and advisory members in the Western Hemisphere and it is believed that the present offers a special opportunity to advance the objectives of the Commission in this Hemisphere. In this enterprise the Commission is assured of the cooperation of both the Pan-American Union and the Office of the Coordinator of Inter-American Affairs.

Plans have been made for Dr. Sayre and one technical assistant to go to Central and South America in the near future to make specific ground-water investigations for the Division of Health and Sanitation of the office of the Coordinator of Inter-American Affairs, and it is hoped that this assignment will give Dr. Sayre opportunity to make helpful personal contacts. It is noteworthy that three hydrologists with wide experience in Latin American countries have recently been elected to membership in the American Geophysical Union. One of these is PEDRO J. AGUERREVERE, one of our advisory members from Venezuela; the other two are GEORGE C. BUNKER and H. T. SMITH, both of whom are citizens of the United States with long service in Latin American countries. Plans are being considered for holding a Pan American conference on ground water, probably after the war and preferably in conjunction with some other Pan American scientific meetings.

It is believed that our Commission can be of material service to the hydrologists of the Latin American countries in their great task of the further development of their ground-water resources for beneficial use. Of major importance in the advancement of sanitation will be the development of public water-supplies for many of the smaller communities from drilled wells.

U. S. Geological Survey,
Washington, D. C.

APPENDIX B--THE WORK OF THE GEOLOGICAL SURVEY AND COOPERATING STATE AGENCIES ON GROUND WATER FOR WAR PURPOSES

O. E. Meinzer

The very large service which the geologists and engineers trained in ground-water hydrology are rendering in this country in the prosecution of the war is due largely to the effective organization for this purpose. The Federal agency in which this service centers is the Water Resources Branch of the United States Geological Survey. The Ground Water Division of this branch has a technical personnel of nearly 100 geologists, engineers, and physicists, and its work is supported by the chemists of the Quality of Water Division and the engineers of the other Divisions of the Branch. It functions through a central office in Washington and 25 widely distributed field-offices. Moreover, this service is effectively supported by the State Geological surveys, State Engineer offices, and other State agencies concerned with water-resources, not only in the 34 States in which there is formal cooperation with the Federal Geological Survey in ground-water investigations but also in those States in which there are no formal cooperative agreements. The magnitude of the civilian service rendered is indicated by the fact that to date about 1,600 reports on

water-supplies from wells have been made to the War and Navy Departments and other war agencies by the Geological Survey and cooperating State organizations.

The plans for this work were based on the experience in the last war. The leadership was taken by DAVID G. THOMPSON, up to the time of his final illness, and he brought to it not only his 25 years of experience in ground-water investigations in all parts of the country but also his valuable experience in the last war. General plans were made as early as September, 1939, and about 500 reports on water-supplies from wells for defense-projects were made prior to the Pearl Harbor attack on December 7, 1941. Many contacts were made with the War and Navy Departments, Office of Production Management, War Production Board, and other Federal agencies and with consulting engineers and contractors on the Federal jobs. Requests for assistance were received in unexpectedly large numbers, all of them urgent and many of them very important, often involving several million gallons of water a day.

The war is to a large extent being run on water obtained from wells. Where adequate ground-water supplies exist, they can generally be developed rapidly and with the use of relatively small amounts of material by constructing wells and filtration is generally not required. Because ground water has a relatively low temperature in summer, it is particularly in demand where any cooling process is required, as in the cooling of generating equipment, cooling-rolls in steel mills, testing airplane engines, and air-conditioning of buildings. Because it is nearly constant in mineral content it is preferred in some manufacturing processes. For these reasons a large part of the war industries are using ground water. Large quantities of ground water are being used at plants that produce explosives, ammonia, glycerine, magnesium, and steel, whereas smaller quantities are being used at countless other war plants.

Large supplies of ground water are also required at many military and naval establishments, some of which have been placed in localities where previously water had been used in only small quantities, and some of which are in coastal areas, where much of the water is salty, or in desert areas where water-supplies may be scant. Increased water-supplies are also needed in many communities with rapid growth near large military establishments or war industries.

Many of the requests came to the Geological Survey in Washington and many others to the State Geological surveys and other State agencies or to the field-offices of the Federal Survey. Close contact was maintained between the Washington office and the field-agencies, and extreme effort was made to submit reports very promptly and yet to have them sound and helpful. As far as possible, the different projects were followed through the stages of testing and development and arrangements were made to obtain records of pumpage and water-level fluctuations in order to know in advance where critical problems of water-supply are likely to develop and to have adequate data for dealing effectively with these problems. In several of the districts of the Army Engineers there is now a definite arrangement whereby the Geological Survey advises on the water-supply problems of the Army establishments and obtains their well-data for study and preservation.

In many places the ground water is well adapted for emergency supplies in case of attack and existing wells might be very helpful if specific information as to their location, yield, and pumping equipment were at hand. In several States reports on emergency supplies have been made to the Navy Department.

A large amount of systematic work has been done by the Geological Survey for the Army, Navy, and other agencies on ground-water supplies for war needs in foreign countries, including office-research and also field-work in the Latin American countries, the West Indies, and the islands of the Pacific.

The Geological Survey has also assisted the Navy Department in preparing a manual on water-supplies from wells for the use of several hundred engineers in the construction battalions.

Early in the emergency, Lieutenant-Colonel GEORGE H. TAYLOR, who had many years of service in the Ground Water Division, was transferred to the Army Engineers and assigned to Washington to act as liaison officer between the Army and the Geological Survey in matters concerning water-supply, and to prepare a section on ground water for the Army water-supply manual and to help select well-drilling equipment for use overseas. In that capacity he has functioned effectively along with the performance of other important duties.

The Army has thus far requested the Geological Survey for a total of 13 geologists to be commissioned for military service with respect to the development of ground-water supplies. In

response, ten geologists of the Ground Water Division have been commissioned and several geologists who are not in the Geological Survey have been recommended. Several of the ground-water geologists are attached to general staffs of overseas armies or have special assignments; the rest are officers in water-supply battalions. It is understood that each water-supply battalion is to have one geologist on its official staff. Several of these are now with the troops in different parts of the world and the others are with units that are being trained for overseas service.

The following ground-water geologists from the Geological Survey have been commissioned: Major R. C. CADY; Captains R. M. LEGGETTE and H. E. THOMAS; and Lieutenants F. C. FOLEY, R. L. NACE, R. C. NEWCOMB, S. L. SCHOFF, R. C. BAKER, BERNARD FISHER, and W. C. RASMUSSEN. Lieutenant-Colonel Taylor's service has already been mentioned. Lieutenant A. P. GERARDI, a ground-water engineer from the Geological Survey, is doing responsible water-supply work overseas.

The first of these geologists to enter military service was Major Cady, who went overseas about a year ago and rendered valuable service in locating well-sites for water-supplies for military operations in parts of Africa and Asia. He died on January 15, 1943, as a result of accidental injuries received January 3.

Unofficial information has been received that some of the ground-water geologists landed with the first troops in North Africa and have rendered service in the development of water-supplies for the Army; also that drilling rigs were landed promptly and were used in putting down successful wells for water-supply within the first few days of the military occupation.

U. S. Geological Survey,
Washington, D. C.

APPENDIX C--REPORT ON RESEARCH IN THE FIELD OF GROUND WATER BEING CONDUCTED BY OIL COMPANIES

N. A. Rose

In view of the shortness of time since the appointment of the writer to the Committee on Ground Water this report is confined to the technology and problems in the Gulf Coast Oil Province. Of course, many of the methods and practices would apply to most parts of the country; however, some would differ materially from one region to another. The writer wishes to acknowledge the suggestions and comments by F. H. LAHEE and PAUL WEAVER.

Having been stationed in Houston, Texas, in the heart of the Gulf Coast Area for four and a half years, the writer has had an opportunity to view the great similarity of the problems confronting the petroleum geologist and engineer and the ground-water hydrologist. Both groups deal with the accumulation, movement, and withdrawal of fluid from underground strata, yet each group is content to study its own literature and use its own terminology without much concern for the other. The petroleum and ground-water engineer, independently of one another, have developed mathematical formulas for the determination of permeability from field-data. These formulas use the same basic principles of physics and the initial papers on the subject by both groups were published within two years of one another. Because of the similarity in the technology and problems of the petroleum engineer and the ground-water hydrologist there is a definite need for closer cooperation. Some of the problems are so closely related that their solution rests in cooperative studies.

A good example of the border-land problems is the study of the mechanics of the formation of salt-domes by Dr. MARCUS A. HANNA of the Gulf Production Company. According to Dr. Hanna ground water plays a very important part in the formation of salt-overhangs. The ground water moves under artesian pressure toward the salt-dome and thence upward along the gouge-zone between the salt and the adjoining strata until its pressure is dissipated or it escapes through crevices above the dome. When the salt is encountered by the water extremely large amounts are dissolved. As this process continues more and more salt is dissolved thus forming an overhang. All known overhangs occur opposite water-bearing sands where the salt is exposed to the dissolving action of circulating waters. According to Dr. Hanna the only possibility for contamination of fresh-water by highly mineralized water from a salt-dome would be directly above a dome by the escape of water through fractures into the overlying fresh-water sands.

The following is a generalized statement on the data obtained by the oil companies in their programs of exploration and in the drilling of wells for oil and gas.

Many of the companies obtain complete stratigraphic information from the surface down to the horizons from which oil and gas are produced. Generally electrical logs are not run from the surface down but begin at the bottom of the surface-casing which in some areas is as deep as 4,000 feet. In areas where complex stratigraphic problems are encountered most of the wildcat wells are electrically logged from the surface, thus providing valuable information on the shallow water-bearing formations. In some areas geophysical work is supplemented by shallow core drilling. Drill-cuttings and electrical logs are obtained from the core-holes which usually are drilled to depths of from 300 to 700 feet.

A special study that is closely related to ground water is the investigation of methods of pumping oil-field waters back into the reservoir-sands. The purpose of the salt-water disposal plants is to eliminate the necessity for surface-storage for such water and the possibility of contamination of surface-streams and shallow ground-water. Several disposal plants are in operation and the number is increasing rapidly. Some of the plants in the East Texas Field will dispose of 500,000 barrels of water a day (14,600 gallons a minute). The water produced together with the oil and gas is injected through special wells into the same formation from which it is being produced but outside of the producing area or injected into strata other than those from which the oil is being produced. If the water is to be injected into another formation it is necessary to determine the depth at which the water becomes brackish or salty, so that permeable beds having no value as a source of water-supply can be used. It is also necessary to study the chemical character of the water to be injected and the persistence of bacteria after injection. If the bacteria remain active underground they cause the formation of deposits in the sand in which the water is being injected and reduce the permeability at a rapid rate and to a considerable degree. A project sponsored by the American Petroleum Institute for the study of the role of bacteria in the formation of hydrocarbons includes an investigation of what bacteria persist after burial of sediments. Since it appears that one class of bacteria are producers of sulfate this investigation may throw some light on the presence of hydrogen sulphide in some water-wells and the corrosive problems caused by this gas in the wells themselves and in the distribution systems.

Several of the oil companies have taken a very active interest in the investigation of ground water in connection with their various operations. Engineers and geologists have been assigned by a few companies to study the ground-water conditions in certain areas. Petroleum engineering in addition to standard ground-water methods are being used in these studies.

In recent years many of the services developed for use in the drilling and completion of oil-wells are being used in water-wells, for example, well cementing, electrical logging, orientation-surveying, selective coring, and the use of special drilling fluids. An interesting development in ground water, which grew out of experiments in oil-fields, is the drilling of horizontal holes from the bottom of a well in order to increase the yield of an aquifer. The original experiment, which was conducted by Mr. RANNEY, caused oil to flow by gravity when the original gas-drive had become ineffective. This method of drilling is widely used in the development of shallow ground-water supplies. On the other hand, some developments for water-wells are becoming standard practice for oil-wells. A good example is gravel-packing, which has been used in the construction of water-wells for about 25 years. However, gravel-packing in oil-wells has become common only in the last five years.

The following papers on petroleum technology should be of interest to the ground-water hydrologist. (The use of the term "reservoir" in some of the titles, which is the equivalent of the hydrologic term "aquifer," is just one example of the individual terminology used by the petroleum engineer and the ground-water hydrologist.)

T. V. MOORE, R. J. SCHILTHUIS, and WILLIAM HURST, The determination of permeability from field data, Amer. Petrol. Inst., Proc. Div. Production, pp. 4-13, May, 1933.

R. J. SCHILTHUIS, Variations in reservoir pressure in the East Texas field, Trans. Amer. Inst. Min. Engs., v. 114, pp. 164-176, 1935.

W. A. BRUCE, Pressure prediction for oil reservoirs, Amer. Inst. Min. Engs., Tech. Pub. No. 1454, March, 1942.

WILLIAM HURST, Water influx into a reservoir and its application to the equation of volumetric balance, Amer. Inst. Min. Engs., Tech. Pub. No. 1473, May, 1942.

W. A. BRUCE, An electrical device for analyzing oil-reservoir behavior, Amer. Inst. Min. Engs., Tech. Pub. No. 1559, January, 1943.

U. S. Geological Survey,
Houston, Texas

REPORT OF COMMITTEE ON RUNOFF, 1942-43

W. G. Hoyt, Chairman

Bertram Barnes
Merrill Bernard
Howard L. Cook
E. S. Cullings
G. A. Hathaway
Karl Jetter
Norbert H. Leupold
Phillip Light
Charles C. McDonald
F. T. Mavis
L. K. Sherman
Waldo E. Smith
Franklin Snyder
H. G. Wilm

The Committee on Runoff was not formally constituted until February 6, 1943, when the members of the Section, as listed above, were asked to serve. At the suggestion of President CHURCH, the Committee has been so selected that there is Nation-wide geographic distribution from West to East with the majority of the Committee composed of younger men.

If the 33 papers prepared for discussion at the regular sessions of the Section of Hydrology at the annual meeting of 1943 can be used as a measure, war instead of curtailing the activities of the Section has acted as an impetus. Also in the field of hydrology as a whole, war activities have apparently not resulted in a decrease of activities. There has been, however, a gradual decrease of activities in the field of research and an increase of activities in the field of applied hydrology. The enormous expansion of our industrial machine and the great concentration of armies and industrial workers into restricted areas; the demands for water, for power, for food and for municipal use; and operations underlying many of our war efforts, secret and otherwise--all these have created problems requiring the full-time effort of hydrologists, both in private and governmental service. It is with some degree of satisfaction that each one of us can feel that either as a result of our past research or in our present positions we have been or are doing our bit to win the war.

Reduction in research activities as a result of the war--For the Forest Service, Dr. CHARLES R. HURSH (Appalachian Forest Experiment Station, Asheville, North Carolina) reports that research in general has been curtailed as a war emergency but where continuing hydrologic studies have already been in progress for several years, an effort is being made to preserve the continuity of the field-records. This is true especially for the watershed-management studies. Analysis of records may be delayed because of lack of trained personnel.

With respect to the Soil Conservation Service, WALDO E. SMITH advises that for the most part, runoff-measurement operations at all field-stations have been continued about as heretofore but that in general observations of runoff from small agricultural watersheds have been terminated.

A research project relating to compilation of flood-volumes, being carried on by the Geological Survey at Pittsburgh, under Works Projects Administration, in cooperation with the Weather Bureau, was discontinued during the year and all personnel transferred to projects relating directly to war activities. The regular stream-gaging program of the Survey has been curtailed but little.

CARROLL F. MERRIAM (Pennsylvania Water and Power Company, Baltimore, Maryland) reports that in spite of war conditions his company is endeavoring to carry on its program of hydrologic research encouraged by the fact that a recent advance has actually played a part in the war effort by enabling them to foresee sufficient river-flow to be able to count upon holding out their steam-equipment for maintenance longer than would otherwise be done. Incidentally, in connection with problems of operation, the Pennsylvania Water and Power Company has inaugurated a punch-card system whereby the daily discharge at 21 gaging-stations in the Susquehanna River System can be analyzed readily in almost every conceivable form.

HOWARD L. COOK (Flood-Control-Survey Organization, Department of Agriculture, Washington, D. C.) reports that the most difficult hydrologic problems with which his organization has had to deal during the past year have arisen from attempts to estimate the effect of treatment of land upon floods from areas in which the capacity of the soil-mantle to store infiltrated water is so small that a substantial proportion of the volume of damaging flood-flows is derived from subsurface runoff. Methods have been devised by which an approximate determination may be made of the effect of changing the type or quality of vegetal cover on the flood-flows from such thin-soiled areas.

Floods--During the year (April, 1942, through March, 1943) the most notable floods in the summer were those which occurred during July, August, and September. The floods of June and

August in the Central West from Minnesota to Oklahoma were the greatest in areal extent. Streams in that region were high all summer and many new flood-records were set. Also of broad extent were the floods of May which covered an area reaching from southeastern British Columbia across Montana, North Dakota, and northwestern Wisconsin. The outstanding flood of last summer was that of July 17-18 in northwestern Pennsylvania. Investigations in the field indicate that precipitation and discharge approached and may have exceeded previous maxima in northeastern United States for equal duration and area. Overnight precipitation in excess of 20 inches is reliably reported and discharges exceeded 2,000 second-feet per square mile from areas of one square mile or less. There appears little doubt that within an area of at least 500 square miles the precipitation was the greatest by far ever recorded for 12- to 18-hour storms in Pennsylvania and has exceeded that recorded previously in northeastern United States. The Allegheny River discharged a runoff-volume of 7.5 inches in five days from 550 square miles, approaching the maximum five-day volume discharged by any river in this region. The October flood in the Potomac and Rappahannock river-basins broke long-time records.

In the Northwest, more especially southern Oregon and California, floods have persisted for almost five out of the six months October through March.

During December rather severe floods occurred in the Ohio, Tennessee, and tributaries. Long-time records were not exceeded. The flood in December, however, was one of the earliest winter floods on record.

Other record-breaking floods occurred in the Humboldt River Basin, Nevada, and in eastern Oregon during February.

As of March 1, snow-cover in the Adirondack Mountains, New York, parts of Quebec and Ontario, Montana, Wyoming, Idaho, Oregon, Washington, and British Columbia was maximum of record, creating a possible flood-hazard in these areas, depending of course on behavior of temperature and synchronization of warm rains during the spring.

Bibliography--Among important contributions in the field of runoff-phenomena during the year should be mentioned: The office manual prepared by RAY C. LINSLEY, Jr., of the United States Weather Bureau, entitled "River forecasting methods;" three articles published in the Proceedings of the American Society of Civil Engineers, namely, "Early contributions to Mississippi River hydrology" by C. S. JARVIS, "Statistical analyses and hydrology" by L. R. BEARD, and "The primary role of meteorology in flood forecasting problems" by MERRILL BERNARD. Reference should be made also to the paper presented at the January meeting of the American Society by G. A. HATHAWAY, entitled "Design of air field facilities." In this connection Mr. Hathaway advises that so far as the United States Engineer Department is concerned, nearly all research activities during the past year have been directed towards problems relating to air-field design, especially problems involving runoff and drainage.

It is a pleasure to report that the Soil Conservation Service has made active progress in making available the results of observations at their experiment stations. During the year Bulletins 2, 3, and 4 were published containing the results of observations at their experimental watersheds at Waco, Texas, Hastings, Nebraska, and Coshocton, Ohio. Bulletin 5, a detailed description of the agriculture soils and geology and topography of the Blacklands Experimental Watershed in Texas is in press and within the present calendar year it is expected that Bulletin 6 containing rainfall-runoff data for the Mexican Springs Area may be made available.

During the year the State of Pennsylvania in cooperation with the Geological Survey and other agencies issued a report describing events associated with the flood of May in 1942 in northeastern Pennsylvania and have in progress a report on the outstanding flood in July in northwestern Pennsylvania. In the Geological Survey two manuscripts have practically been completed describing the floods of 1938 in Texas and the floods of 1940 in the southeastern States.

It is with some personal pride that I mention the Water Resources Review, published monthly by the Geological Survey. Since the first of the year this Review covers Canadian conditions as well as the United States and we are thus able to present monthly a condensed summary of surface, ground-water, and storage-conditions throughout the United States and Canada. The inclusion of Canadian data has been made possible through the wholehearted collaboration and cooperation of the Dominion Water and Power Bureau.

U. S. Geological Survey,
Washington, D. C.

REPORT OF COMMITTEE ON LAKES, 1942-43

S. T. Harding, Chairman

This Committee is the successor to the former Committee on Physical Limnology. The Chairman was notified of his appointment in February, 1943, and the Committee is still in the process of formation.

The field of activity of this Committee has not as yet been fully defined and the particular subjects on which it may work have not been selected. Suggestions regarding such subjects and the names of members interested in this field will be welcome.

In general our field is considered to include all hydrologic problems relating to lakes except those directly within the field of other Committees. Evaporation from lakes is within the field of the Committee on Evaporation and Transpiration.

The extent of our activities will be determined by the time its members may be able to devote to its work. During the war it is expected that it will be necessary to adjust the program of the Committee to the time its members may be able to spend on its work.

University of California,
Berkeley 4, California

THUNDER-STORMS AND RUNOFF AT HIGH ELEVATIONS IN NORTHWESTERN NEW MEXICO

L. L. Harrold

The following statements are based on data collected and prepared for publication in the Hydrologic Bulletin series of the Department of Agriculture by A. J. DICKSON at the Navajo Experiment Station.

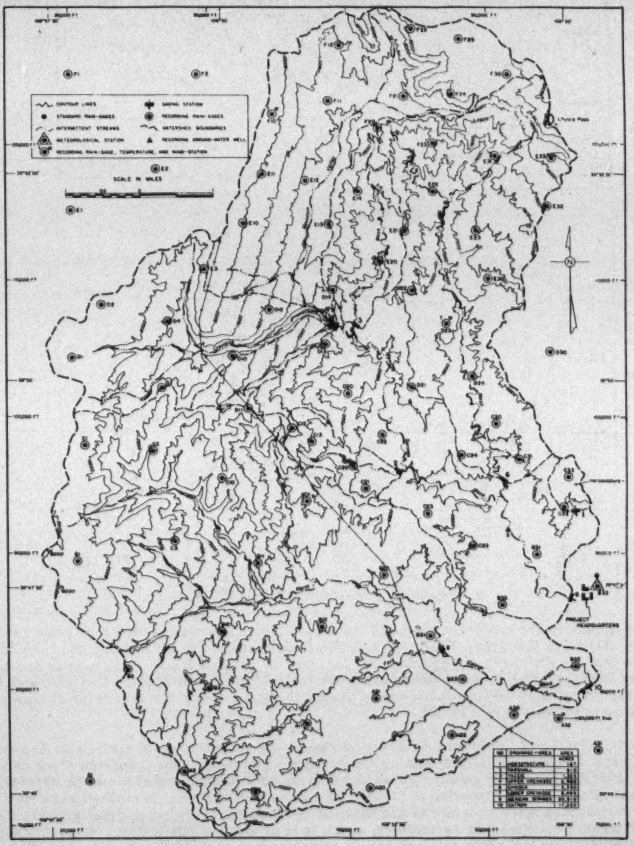


Fig. 1--Topographic map of the watersheds

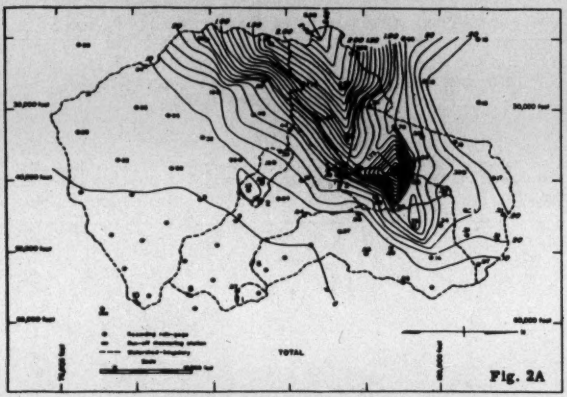


Fig. 2A

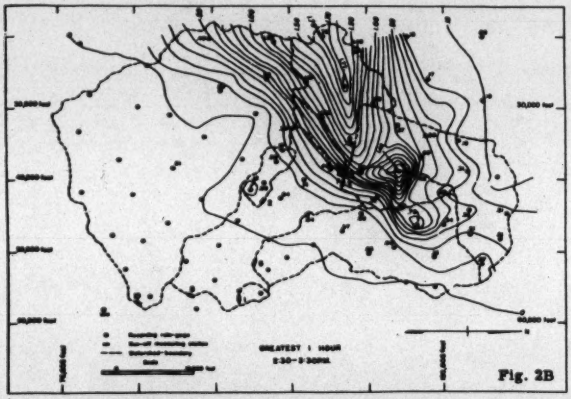


Fig. 2B

Fig. 2--Isohyetal maps, storm of July 23, 1941

Water-supply in the southwest region of the United States has always been a problem to those living or traveling in that area. Water for household uses, stock, and agriculture has been sought both on the surface and below the ground. The fact that all but the largest stream-beds are dry most of the time, and that summer floods are noted for the rapidity with which they rise and recede and for the large debris-load they carry, makes the planning for surface-water conservation, irrigation, and drainage very difficult.

LEOPOLD [see 1 of "References" at end of paper] has recently added much to the knowledge of rainfall over large areas in New Mexico and Arizona. The paper here presented gives detailed examples of rainfall-data for smaller areas and data on the resulting runoff from the watersheds of the Navajo Conservation Experiment Station, 20 miles north of Gallup in northwestern New Mexico. A description of these watersheds and data for 1941 appear in Hydrologic Bulletin No. 6 of the United States Department of Agriculture, which is in process of publication. A brief description of the watersheds for which data are herein given appears at the end of this paper. These watersheds range up to about 21,000 acres in size and are in rough mountainous country (Fig. 1)

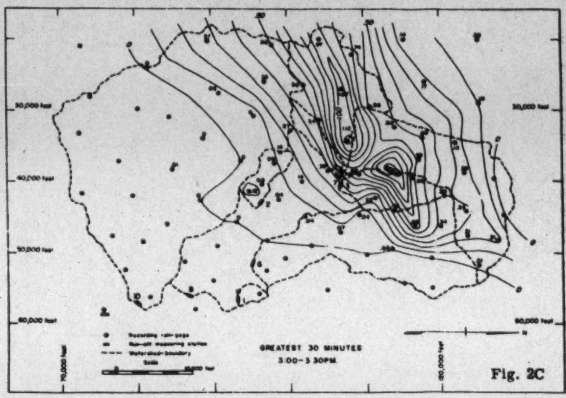


Fig. 2C

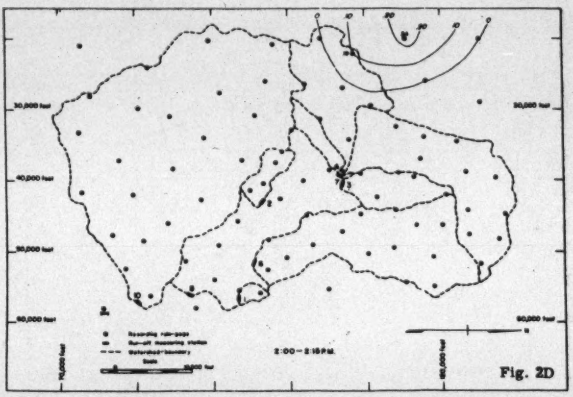
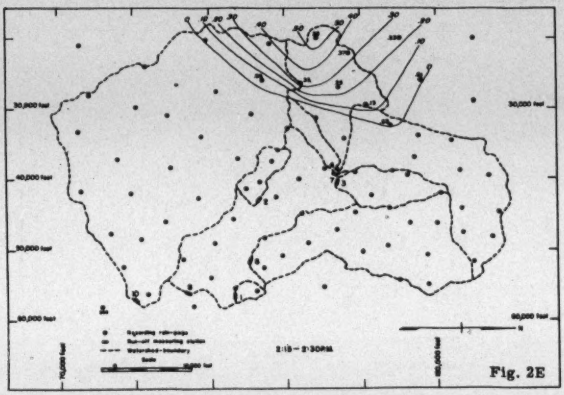


Fig. 2D

Fig. 2--Isohyetal maps, storm of July 23, 1941

at elevations ranging from about 6,300 to 8,800 feet. The annual precipitation for the seven-year period of rainfall-records at station F10, elevation 8,014 feet, averaged about 18 inches, which is about four inches higher than that of the 92-year record at Santa Fe, New Mexico, elevation 7,013 feet. Rainfall averaged nine inches each for the six-month periods of summer to fall, which is about normal, and of winter to spring, which is three inches above normal. Precipitation in winter is light and usually in the form of snow. Rain in spring and early summer falls at low intensities and seldom results in runoff. During July and August, when the watersheds usually receive about one-fourth of the average annual rainfall, the storms are of the convective type and thus produce high rates of rainfall in erratic local patterns and are frequently accompanied by hail. Isohyetal maps (Fig. 2) for one of these typical thunder-storms, July 23, 1941, show by 15-minute periods its metamorphosis and dissipation within the limits of the area gaged by rainfall-stations, about 44,000 acres.

The storm first made its appearance in the area along the western ridge and considerable rain fell in Upper Crevasse Watershed and headwaters of Catron Watershed from $2^h\ 15^m$ to $3^h\ 00^m$ p.m. before significant rain was observed farther to the east. The rainfall for the next 15 minutes,



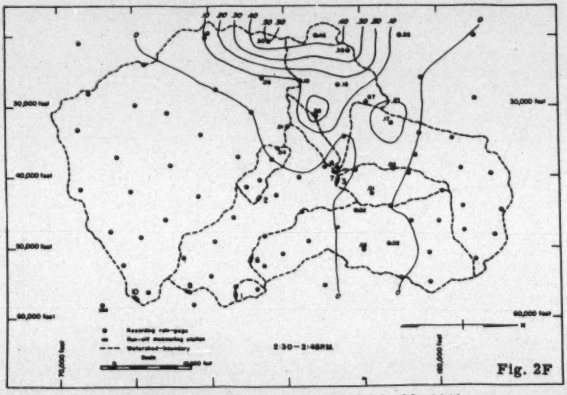
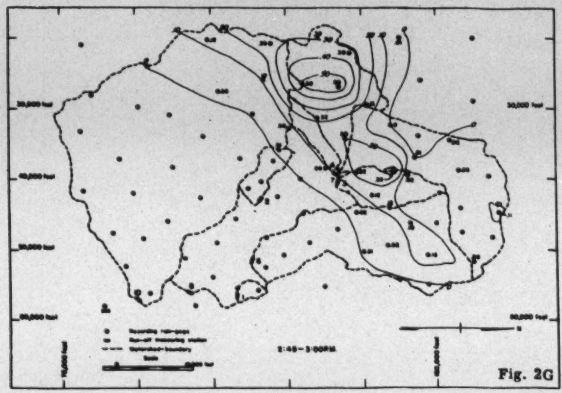


Fig. 2--Isohyetal maps, storm of July 23, 1941

$3^h\ 00^m$ to $3^h\ 15^m$ p.m., over Upper Crevasse, Mountain Valley, Yazzie, and the headwaters of Chusca watersheds was extremely heavy, reaching a maximum 15-minute rate of 3.8 inches per hour. The highest amount of rainfall for the storm was 2.40 inches, recorded at station D1 on the western boundary of the area. Rain along the central section of this ridge continued at a high rate for the hour $2^h\ 15^m$ to $3^h\ 15^m$ p.m. and then slacked off rather quickly. After $3^h\ 30^m$ p.m. the greatest amount of rain recorded in 15 minutes on the watersheds was not over 0.06 inch, except for an isolated shower over Horsepasture Watershed.

Although the gages are spaced about one mile apart and each gage has a Thiessen area of application of about 530 acres, a few additional rain-gages strategically located would have helped establish the position of some of the isohyetal lines. A study of the isohyetal lines on Figure 2 will indicate the difficulty of establishing in this region accurate isohyetal maps for this type of storm and determining time-area-depth and rainfall-runoff relationships for thunder-storms with rain-gages spaced much farther apart. As the isohyetal lines of this storm do not close within the area, it is not possible to derive time-area-depth curves.



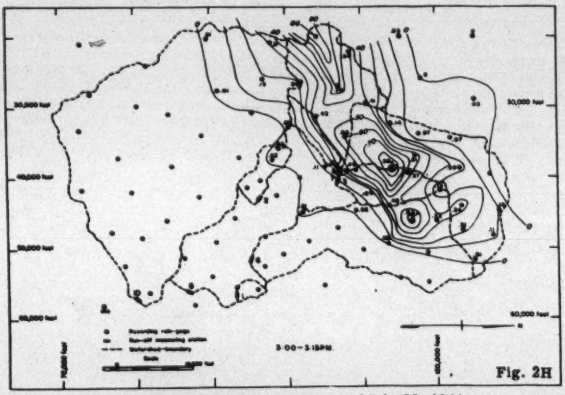


Fig. 2--Isohyetal maps, storm of July 23, 1941

Five other major runoff-periods occurred in 1941, all in summer and fall. A sufficient number of isohyetal lines closed within the area for only two of these storms, August 6 (Fig. 3) and 15, to permit the computation of time-area-depth curves (Fig. 4). These curves show the areal extent of greatest average depth for maximum 15-, 30-, and 60-minute periods. The lower-depth isohyetal lines extended beyond the boundary of the area gaged, thus limiting the computations to average depths above 0.5 inch, except for the maximum 15-minute period, August 6, which could be carried down to 0.25 inch. The largest rainfall-depths for the maximum 15-, 30-, and 60-minute periods for August 6 were 0.67, 0.84, and 0.95 inch, respectively. These depths are low compared with similar ones of 0.96 inch, and 1.12 and 1.77 inches for the storm of July 23 (Fig. 2).

Although during 1941 there were 20 days when at least one gage recorded excessive rates of rainfall, no gage recorded excessive rainfall on more than five days. (Rainfall-depth greater than 0.20 inch, plus the product of 0.01 inch times the duration in minutes [0.25 inch in five minutes, 0.30 inch in ten minutes, or 0.80 inch in one hour, etc.], is defined as excessive.) Six gages (D4, F21, D3, E21, D10, E14) recorded excessive rainfall on five days. On August 15, 46 gages, covering more than 20,000 acres, recorded excessive rainfall.

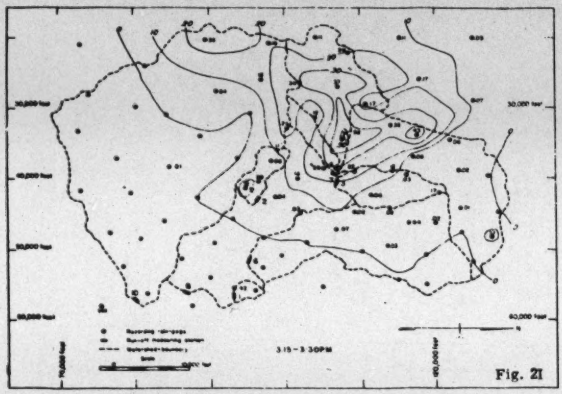


Fig. 2--Isohyetal maps, storm of July 23, 1941

With high rates of rainfall occurring so spasmodically in time and area, it must be a rare occasion when the entire Mexican Springs Watershed of 20,910 acres contributes runoff to a single flood. An inspection of the hydrographs (Figs. 5 to 7) from Yazzie, Chusca, and Mexican Springs watersheds, along with the time and approximate rate of the peak for Lower Crevasse and Parshall watersheds, indicates the part these subareas had in the development of the hydrograph for the entire area of Mexican Springs Watershed. As entire hydrographs are not available for Lower Crevasse and Parshall stations, it is not possible to complete the picture of subarea contribution. A study, however, of the peak-rates and time of their occurrence reveals interesting features of

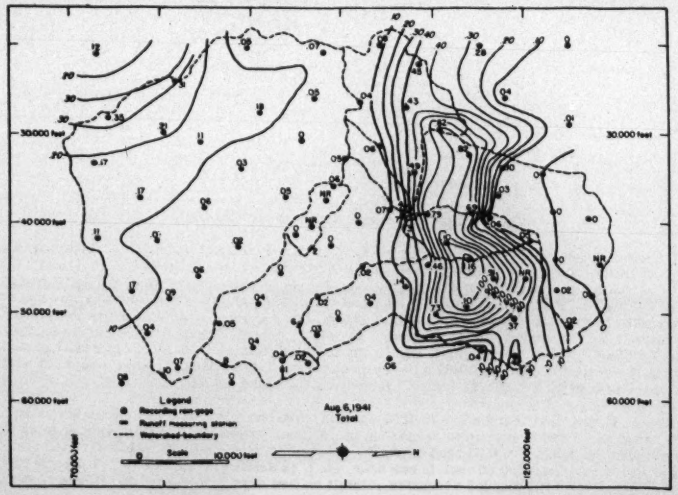


Fig. 3--Isohyetal map of total rainfall, August 6, 1941

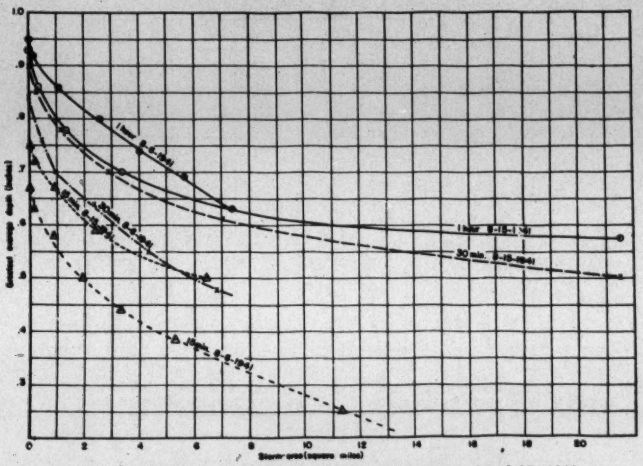


Fig. 4--Time-area-depth curves, storms of August 6 and 15, 1941

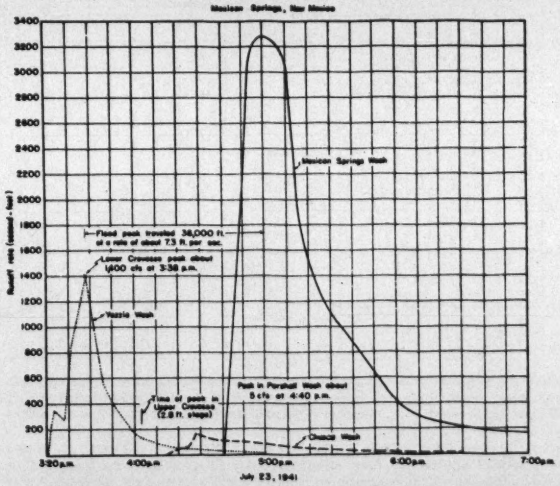

Mexican Springs, New Mexico
Mexican Springs Wash
Flood peak traveled 36,000 ft. at a rate of about 7.3 ft. per sec.
Lower Crossing peak about 1400 cfs at 3:38 p.m.
Yazzie Wash
Time of peak in Upper Crossing (2.8 ft. stage)
Peak in Pinabetl Wash about 5 cfs at 4:40 p.m.
Chusca Wash
3:20 p.m.
4:00 p.m.
5:00 p.m.
6:00 p.m.
7:00 p.m.
July 23, 1941

Fig. 5--Hydrograph comparison and flood-travel, July 23, 1941 (total runoff for Yazzie Watershed 36.7, Chusca 1.4, and Mexican Springs 266 acre-feet)

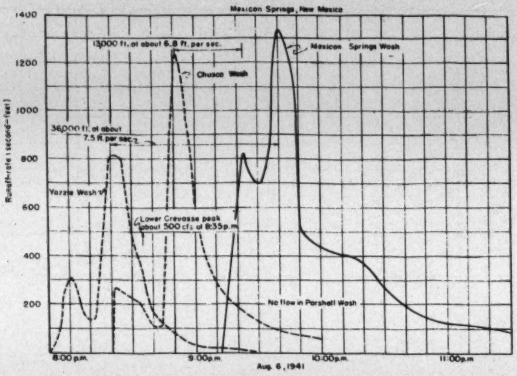


Fig. 6--Hydrograph comparison and flood-travel, August 6, 1941 (total runoff for Yazzie Watershed 33.7, Chusca 56.9, and Mexican Springs 102 acre-feet)

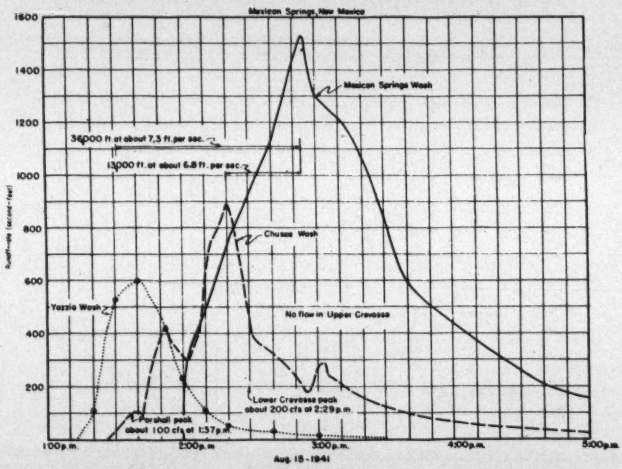


Fig. 7--Hydrograph comparison and flood-travel, August 15, 1941 (total runoff for Yazzie Watershed 32.7, Chusca 71.2, and Mexican Springs 202 acre-feet)

flood-peak travel. For example, on July 23, 1941 (Fig. 5), the peaks of Yazzie and Lower Crevasse watersheds, each about 1,400 second-feet, simultaneously reached their confluence a short distance below their gaging-stations. To this combined peak of 2,800 second-feet was added only small flow as it passed downstream through 36,000 feet of channel to the Mexican Springs Station, yet the peak measured at this lowest station was 3,270 second-feet. The velocity of the travel of the peak is faster than the wave-front in the dry stream-channel and there is a tendency for water in the peak to override the water in front. The channel-storage in this reach has, however, a tendency to reduce the peak-rate. The wave-front is a moving debris-dam of sticks, pine-cones and needles, mud and other debris. The average velocity of travel of the July 23 flood-peak (Fig. 5) of about

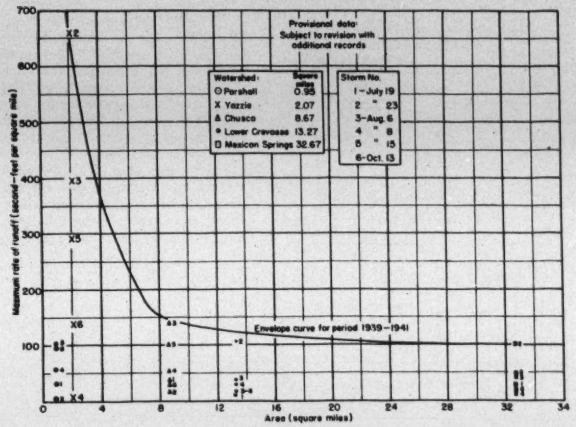


Fig. 8--Peak-flows, 1941

seven feet per second in this 36,000-foot reach of channel is about the same as that for the large floods shown in Figures 6 and 7.

A study of the isohyetal map (Fig. 2) and the hydrographs (Fig. 5) for the storm of July 23 reveals that of the 266 acre-feet (0.153 inch) of runoff that passed through the Mexican Springs Gaging-Station, 36.7 (0.333 inch) came from Yazzie Watershed and 1.4 acre-feet (0.0031 inch) came from Chusca Watershed. The area below Crevasse Canyon and southwest of Mexican Springs Wash yielded very little runoff-water to this flow. Although the hydrographs for the Crevasse gaging-stations are not available and there is probably some water-loss in channel below Yazzie and Crevasse stations, it seems reasonable to assume that most of the runoff from the ungaged area, over 200 acre-feet of water, passed through the Lower Crevasse Station. A volume of 200 acre-feet is equivalent to an average depth of 0.28 inch over the 8,495-acre drainage-area, which depth is 0.05 inch less than that for Yazzie Watershed.

A similar study of the isohyetal map (Fig. 3) and the hydrographs (Fig. 6) for the storm of August 6 reveals that of the 102 acre-feet (0.0584 inch) of runoff that passed through the Mexican Springs Gaging-Station, 33.7 (0.305 inch) came from Yazzie Watershed and 56.9 acre-feet (0.122 inch) came from Chusca Watershed. The area below Crevasse Canyon and southwest of Mexican Springs Wash probably yielded no runoff. It seems reasonable to assume that all of the runoff from the ungaged area, over ten acre-feet, passed through the Lower Crevasse Station. It is likely that more than ten acre-feet (ten acre-feet equals 0.014-inch depth on the 8,495-acre area) passed the Lower Crevasse Station, as there was probably some loss in the channel of the Mexican Springs Wash.

The rain of August 15 was more general over the entire 20,910-acre Mexican Springs Watershed than the storms of July 23 and August 6 described above. Runoff for this entire area on August 15 was 202 acre-feet (0.116 inch), of which 32.7 (0.296 inch) came from Yazzie Watershed and 71.2 acre-feet (0.154 inch) came from Chusca Watershed. The ungaged area yielded 98 acre-feet or 0.085-inch average depth on 14,000 acres, making no allowance for losses in dry reaches of channel.

The peak-rates of runoff per unit-area during 1941 are shown on Figure 8. Peak-rates for storms other than those for 1941 are not plotted because they are too small. It can be readily seen that the peak for Yazzie Watershed, July 23, of 660 second-feet per square mile (1.03 inch per hour) is the only one of great magnitude. The maximum half-hour point-rainfall on Yazzie Watershed for this storm was 2.3 inches per hour [25-year recurrence-interval, according to Yarnell, 2] and the weighted average over the drainage of 1,325 acres for the same period was about 1.1 inches per hour [two-year point-recurrence].

Rainfall-station	Thiessen areal weight-factor	Amount of rain that fell over 1.05 inch per hour	
		Actual	Weighted
		inch	inch
F20	0.08	0.07	0.006
E21	0.10	0.27	0.027
E20	0.24	0.03	0.007
E14	0.27	0.47	0.127
E13	0.11	0.83	0.091
D14	0.20	0.38	0.076
Total	1.00	.....	0.334

The hydrograph of runoff for Yazzie Watershed for the storm of July 23, 1941, may be compared with corresponding graphs of rainfall-rates for each rain-gage on the watershed (Fig. 1) and the weighted (Thiessen) average rates on Figure 9. Thiessen areal weight-figures for each gage and the curve of weighted average rainfall-amount over and above certain rates of rainfall are also shown. Points for this weighted average rainfall-excess versus intensity curve were derived as in table, using 1.05 inch per hour intensity as an example.

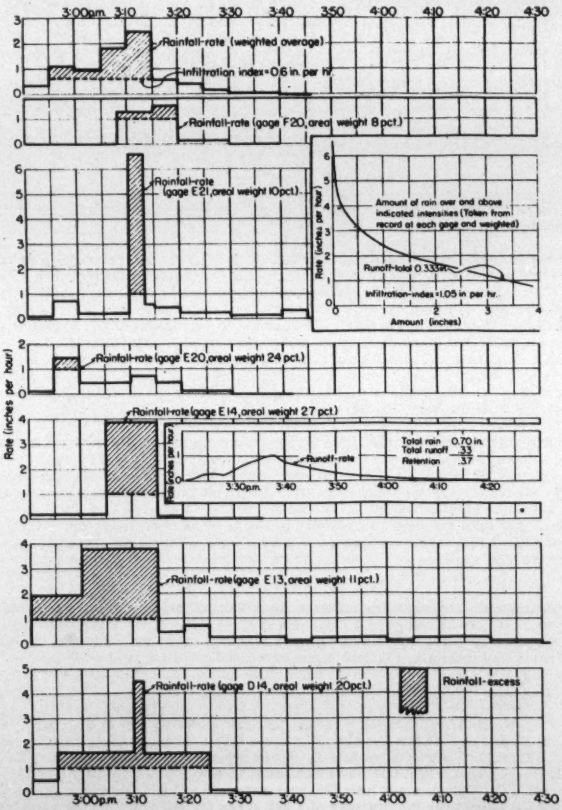


Fig. 9--Rainfall and runoff, Yazzie Watershed (drainage-area 1325 acres), July 23, 1941

The amount of rain that fell over and above the intensity of 1.05 inches per hour at all six rainfall-stations averaged 0.334 inch on the Yazzie Watershed of 1,325 acres. Using this derived curve (weighted average rainfall-excess versus intensity) it is possible to determine the rainfall-rate such that the rainfall-amount above this rate equals the amount of runoff. This rate is called "infiltration-index." It may also be called the "average retention-rate." Entering the curve with the runoff of 0.333 inch, the index is found to be 1.05 inches per hour. This index of 1.05 inches per hour more nearly represents the actual infiltration-rate than does the rate of 0.6 inch per hour determined from the weighted average rainfall-rate graph at top of Figure 9. No attempt has been made to determine the shape of the infiltration-curves.

Weighted curves of rainfall-excess versus intensity derived as explained above are useful in determining the infiltration-indices for watersheds having more than one rainfall-station, and the resulting infiltration-index is believed to be more nearly in accord with the true average infiltration-rate than that derived from the weighted average rainfall-graph. The weighted average rainfall-graph for the storm of July 23 is comprised of records at six stations having rainfall-rates both above and below the infiltration-index rate. During two periods, $2^h\ 50^m$ to $2^h\ 55^m$ p.m. and $3^h\ 15^m$ to $3^h\ 25^m$ p.m., the weighted curve is below the index, yet at one or two stations during each period the rate is above the index. In other words, the weighted rainfall-curve would show no rainfall-excess (runoff) for these periods although runoff was actually generated on a portion of Yazzie Watershed. If the rainfall-rate at the six rainfall-stations is above the index continuously and simultaneously, the index will be the same whether it is computed from the weighted average rainfall-graph or from the curve of weighted rainfall-excess versus intensity. Whenever the rate at one gage drops below the index, the index derived by the former method will always be lower than the "truer" index derived by the latter method. The weighted curve of rainfall-excess versus intensity used in this paper is not unlike the "total supply versus infiltration-capacity curve" derived by R. E. HORTON [3], which is compiled from the rainfall-excess at each rainfall-station in the area. Likewise its use for determining infiltration-rates is subject to the same qualifications, that is, (1) infiltration-rates vary with time and location over different parts of the watershed and (2) runoff may not begin when rainfall-excess first occurs due to filling of depression-storage and building up surface-storage which runs off after rainfall-excess stops, and infiltration from overland flow continues for a short time after rainfall-excess stops.

Seasonal and annual rainfall- and runoff-amounts--The total rainfall on these watersheds for the summer-fall season of 1940 and for the year 1940 was about the same as the 92-year mean for the same seasons at Santa Fe, New Mexico. (Although the Santa Fe Rainfall-Station is east of the Continental Divide, its record is used for comparison as it is the largest in the region and compares fairly well with the records at B33 and F10 during 1935-41.) Runoff for this year amounted to 0.13, 0.38, and 0.23 inch for Parshall, Chusca, and Mexican Springs watersheds, respectively. The average runoff over a long period will probably be about the same or somewhat less than that for the summer-fall and the year 1940 (curves A, Figs. 10 and 11). Minimum annual and seasonal

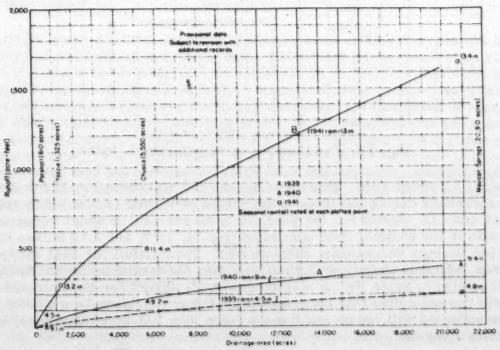


Fig. 10--Summer and fall yield (runoff June to November), 1939-1941

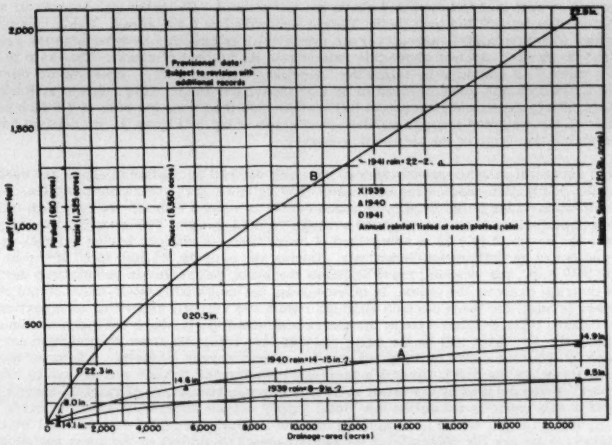


Fig. 11--Annual yield (runoff), 1939-1941

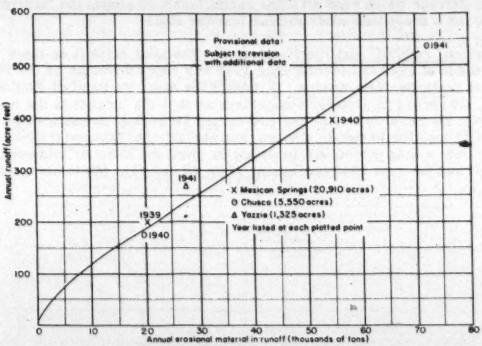


Fig. 12--Erosional material in runoff-water

runoff may frequently approach zero. Maximum annual and maximum runoff for the summer-fall season on these watersheds during the three-year period of record is that which occurred in 1941 (curves B, Figs. 10 and 11). Runoff for the year, 25 to 50 per cent of which occurred in six brief major runoff-periods in the summer-fall, amounted to 2.24, 1.17, and 1.19 inches for Yazzie, Chusca, and Mexican Springs watersheds, respectively. The rainfall for 1941 averaged about 22 inches over the area, which is about four inches less than the maximum annual rainfall recorded during the 92-year period at Santa Fe. A maximum runoff-amount for the year and the summer-fall season somewhat greater than that recorded in 1941 may therefore be expected. The maximum annual runoff to be expected will not be much more (less than 1/2-inch difference) than that of the maximum summer-fall season.

Amounts of annual erosional material--Erosional material in water passing through the runoff-measuring stations (Yazzie, Chusca, and Mexican Springs) is high (Fig. 12), at times reach-

ing 30 per cent of the volume of runoff sampled. The figures of erosional material for the year are slightly low because the runoff was not sampled in some of the smaller runoff-periods. The point for the Mexican Springs Watershed of 2,070 acre-feet is not shown on Figure 12 because the amount of unmeasured erosional material was considerable. Some of the erosional material came from the rough broken lands of Yazzie and Chusca watersheds and some was probable picked up in transit from the beds and banks of the arroyos. Where the velocity of the water is reduced, much of the material is deposited. Reservoirs behind several diversion-dams in this area were completely filled to spillway-crest elevation within a period of one or two years by such deposition. Satisfactory methods of handling large quantities of heavily laden runoff-water in connection with programs for irrigation and water-conservation of the region have yet to be worked out.

Additional years of observation and data at this research station will go far towards acquiring a comprehensive knowledge of small-area thunder-storms in the arid southwest and the resultant runoff and erosion.

Description of Parshall, Yazzie, Chusca, and Mexican Springs watersheds--Parshall Watershed (No. 2) of 610 acres (0.95 square mile) has a 22 per cent crown-coverage of pinon and juniper trees. Elevations range from 6,612 to 7,540 feet. The length of the principal watercourse is 10,400 feet. About 12 per cent of the area has a land-slope of less than ten per cent, 25 per cent from 10 to 30 per cent, 60 per cent from 30 to 60 per cent, and three per cent from 60 to 100 per cent--average land-slope is 36 per cent. All of the area is a residual rough stony land, the greater part of which is composed of exposed sandstone. Shale is exposed to a lesser extent. Runoff-records before 1941 are based on the standard Parshall rating. As the effect of the velocity of approach has not yet been determined, only peak-values are given for 1941. All records for this station may be too low if the effect of the approach-velocity is significant.

Yazzie Watershed (No. 3) of 1,325 acres (2.07 square miles) has a sparse cover of pinon and juniper trees. Elevations on the watersheds range from 6,796 to 7,800 feet. The length of the principal watercourse is 17,700 feet. About 19 per cent of the area has a land-slope of less than ten per cent, 39 per cent from 10 to 30 per cent, 39 per cent from 30 to 60 per cent, and three per cent from 60 to 100 per cent--average land-slope is 30 per cent. About 93 per cent of the area is residual rough broken and stony land, the greater part of which is composed of exposed shales and sandstones, and seven per cent is alluvial soils of Crown sandy loam and sandy clay-loam. Rock-outcrops are numerous. Runoff-records before 1941 are not used.

Chusca Watershed (No. 6) of 5,550 acres (8.68 square miles) has a sparse cover of pinon and juniper trees. Elevations range from 6,507 to 8,795 feet, and the length of the principal watercourse is 42,600 feet. About 23 per cent of the area has a land-slope of less than ten per cent, 43 per cent from 10 to 30 per cent, 23 per cent from 30 to 60 per cent, nine per cent from 60 to 100 per cent, and two per cent of more than 100 per cent--average land-slope is 30 per cent. About 90 per cent of the area is rough broken and stony land, three per cent is Pinedale sandy clay, and seven per cent is Crown sandy loam and sandy clay-loam. Rock-outcrops are less extensive than those in Yazzie Watershed.

Mexican Springs Watershed (No. 8) has a drainage-area of 20,910 acres (32.3 square miles) and includes the three watersheds just described. Elevations on the watershed range from 6,402 to 8,793 feet and the length of the principal watercourse is 70,200 feet. At elevations up to 7,000 feet there is a sparce cover of pinon and juniper trees enclosing areas of sage-brush and of grass. Above 7,000 feet in Crevasse and Mountain Valley watersheds, tributaries of Mexican Springs Wash, there are widely spaced ponderosa-pine trees. Rock-outcrops are very numerous and extensive in these two watersheds. About 34 per cent of the area has a land-slope of less than ten per cent, 43 per cent from 10 to 30 per cent, 17 per cent from 30 to 60 per cent, five per cent from 60 to 100 per cent, and one per cent of more than 100 per cent--average land-slope is 24 per cent. About 73 per cent of the area is rough broken and stony land, 13 per cent is Chusca sandy loam and clay-loam, three per cent is Pinedale sandy clay, and 11 per cent is Crown sandy loam and sandy clay-loam.

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DISCUSSION

G. N. BRANCATO (U. S. Weather Bureau, Washington, D. C.)--Rainfall-distribution in thunder-storms as well as the effect of topography on their development and movement is a problem of considerable interest to both hydrologists and meteorologists. In order to be able to study this type of meteorological phenomenon fully a very dense network of stations would be required, equipped with wind-recorders, hygrographs, and recording rain-gages, over an area large enough to chart both the development and dissipation of the storm. Even though the Mexican Springs Project does not meet all these requirements, there are certain thunder-storm characteristics which can be studied from the rainfall-records over the area.

The thunder-storm of July 23, 1941 (Fig. 2), occurred in tropical air which was flowing over the mountains from a southwesterly direction up to an elevation of about 10,000 feet above mean sea-level. The velocity of the air, as nearly as could be determined from the few stations making upper-air observations, was about nine miles per hour. The successive 15-minute isohyetal maps show that the rainfall spread across the area at about this rate.

The topography along the path of the storm decreases in elevation approximately 1,000 feet from the western boundary of the area of the project to the northeastern corner where it again rises to over 8,600 feet at Chusca Peak. This marked decrease in elevation no doubt at least partially accounts for the dissipation of the storm within the basin which in turn resulted in the rapid decrease of the width of the rainfall-pattern.

The three 15-minute maps from $2^h\ 45^m$ p.m. to $3^h\ 30^m$ p.m. suggest that the upslope motion of the air over the high ridge along the west boundary resulted in a more or less continuous development which was then carried along northeastward with the wind. On the chart for $2^h\ 45^m$ to $3^h\ 00^m$ p.m. it will be noted that the highest 15-minute values were located well east of the ridge. The next chart, $3^h\ 00^m$ to $3^h\ 15^m$ p.m., shows the highest values at the ridge, while the last chart, $3^h\ 15^m$ to $3^h\ 30^m$ p.m., shows the highest values well to the east again. In this, however, the assumption is made that an increase or decrease in intensity or development of the thunder-storm results in an increase or decrease in the intensity of rainfall.

A density of stations such as this gives a very good measure within narrow limits of the width of the rainfall-pattern produced by a single thunder-storm. In Figure 2 the width taken across the direction of motion of the storm at the widest place was approximately eight miles. In Figure 3 the width of the rainfall-pattern produced by the thunder-storm of August 6, 1941, was about four miles. This is in agreement with and further substantiates a study made of the width of thunder-storm rainfall-patterns over the Muskingum Watershed Project in Ohio where this width did not exceed 12 miles.

The isohyetal pattern in Figure 3 was produced by a single thunder-storm which developed near the eastern boundary of the basin and moved westward. As indicated by 15-minute increment maps the rainfall spread across the basin at about eight miles per hour. This is in agreement with the direction and velocity of the air up to above 10,000 feet at this time.

In the progress of the storm westward over the basin the highest amounts of precipitation were experienced at the lowest elevations. The effect of decreasing elevation in this case seems to be opposite to that expected and to that experienced in the thunder-storm of July 23, 1941. The explanation for this is not apparent from surface-observations but an examination of the upper air indicates that the thunder-storm developed as a result of convergence aloft and not from orographic lifting. The effect of downslope motion in the lower layers of the atmosphere could be more than compensated for by convergence aloft so that local topography would not necessarily affect the intensity of the rainfall.

CLASSES AND PATTERNS OF RAINFALL WITH REFERENCE TO SURFACE-RUNOFF

Leonard Schiff

Relation of precipitation, infiltration, and rainfall-excess--This paper deals primarily with rainfall-characteristics. Consideration is given the relationship between rainfall and infiltration and surface-runoff on small watersheds. Excess or supply of rainfall for surface-runoff is dependent upon the duration and order in which rates of rainfall occur and conditions of watershed, and is mainly the difference between the rainfall-rate and infiltration-rate.

The intensities of rainfall and their order or pattern exert a marked influence on the change in conditions of watershed during a storm as well as on antecedent conditions of watershed, and thus on the infiltration-rate. The rapid drop in infiltration-rates caused by "sealing" of the ground-surface through the puddling action of rain-impact and erosion and inworking of fine particles has been well illustrated [see 1 of "References" at end of paper]. Drop-size usually increases with intensity, resulting in greater soil-dispersion and reduced infiltration [2,3]. The amount and location of soil-moisture are also dependent among other things upon the characteristics of rainfall.

The relation between rainfall and surface-runoff has frequently been expressed as a coefficient. For many purposes such coefficients are not as useful in the evaluation of surface-runoff as are precipitation-data used in conjunction with a detailed knowledge of the infiltration-rates to be expected. Considerable information on infiltration is becoming available from the research work of the United States Department of Agriculture.

Establishment of rainfall-classes--The data used for the classification of rainfall based on magnitude of intensities (classes) and the sequence of occurrence of rainfall-intensities (patterns) cover the six-year period of record of the North Appalachian Experimental Watershed, Soil Conservation Service, Coshocton, Ohio. The records show definite trends.

The amounts of rainfall for each storm of 0.25 inch or more were tabulated for all the recording rain-gages shown in Figure 1 for the period of record 1937-42. Rainfall was divided into more

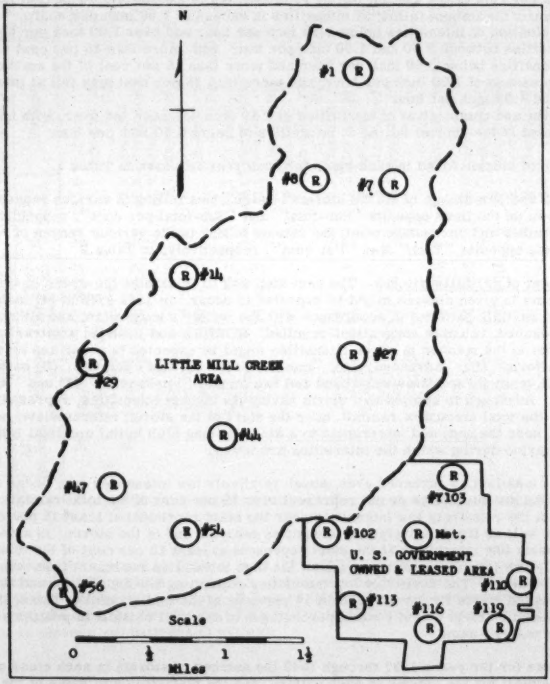

Fig. 1--Chart to show recording rain-gages used (gages indicated by encircled R)

Table 1--Number of storms in each class, 1937-42

Year	Number in each class					Total
	I	II	III	IV	V	
1937	10	20	3	12	13	58
1938	6	10	6	21	8	51
1939	7	20	4	8	13	52
1940	3	18	5	16	12	54
1941	4	10	4	18	11	47
1942	6	14	1	18	14	53
Total	36	92	23	93	71	315

than one storm if a gap of six or more hours occurred during which no rain fell. This might be considered satisfactory for small watersheds and two or more consecutive storms of determined classes and patterns may be combined for overall classifications and application to larger watersheds. The one record selected for analysis for each storm was obtained usually from the gage receiving the greatest catch of rainfall near the center of the storm on the area, appearing accurate and reasonably consistent with other records obtained from gages in the locality.

Each storm was then placed in one of the following arbitrary classes:

Class I--Uniform intensities up to and including 0.50 inch per hour, a deviation of one and one-half times the mean rate permitted for the maximum intensity within a storm

Class II--Combination of intensities up to and including 0.50 inch per hour, with not more than 15 per cent of the amount falling at intensities in excess of 0.50 inch per hour

Class III--Combination of intensities below and above 0.50 inch per hour up to and including 1.00 inch per hour with more than 15 per cent of the amount falling at intensities below 0.50 inch per hour and more than 15 per cent of the amount falling at intensities in excess of 0.50 inch per hour and less than 15 per cent of the amount falling at intensities in excess of 1.00 inch per hour.

Class IV--Combination of intensities below 0.50 inch per hour and over 1.00 inch per hour, may include intensities between 0.50 and 1.00 inch per hour, with more than 15 per cent of the amount falling at intensities below 0.50 inch per hour and more than 15 per cent of the amount falling at intensities in excess of 1.00 inch per hour, and more than 15 per cent may fall at intensities between 0.50 and 1.00 inch per hour.

Class V--Uniform and combination of intensities of 0.50 inch per hour and over, with not more than 15 per cent of the amount falling at intensities to below 0.50 inch per hour

The number of storms found in each class for each year is shown in Table 1.

The number and percentage of all the storms in each class falling in various ranges of total rainfall are shown on the lines opposite "Sub-total" and "Sub-total per cent", respectively, in Table 2. The number and percentage of all the storms falling in the various ranges of rainfall are shown on the lines opposite "Total" and "Per cent", respectively, in Table 2.

Establishment of rainfall-patterns--The next step was to determine the order in which the intensities of storms in given classes might be expected to occur. In 1940 ERWIN [4] included in his thesis a study of rainfall-patterns in accordance with the writer's suggestion, and although no conclusions were reached, valuable suggestions resulted. HORNER and JENS [5] arbitrarily chose intensity-patterns in the manner in which intensities might be expected to occur and referred to them as the "uniform" (U), "advanced" (A), "intermediate" (I), and "delayed" (D) patterns. For the sake of consistency these terms were used and two terms, "interrupted" (T) and "sporadic" (S), were added. Advanced is applied to a storm having its highest intensities, representing 15 per cent or more of the total amount of rainfall, near the start of the storm; intermediate, near the center; delayed, near the end; and interrupted to a storm having high initial and final intensities separated by a period during which the intensities are lower.

A storm is classified as advanced even though relatively low intensities may occur at the start, providing the low intensities do not represent over 15 per cent of the total rainfall. In an intermediate storm the relatively low intensities near the start represent at least 15 per cent of the total rainfall, as well as the relatively low intensities near the end of the storm. In a delayed storm the relatively low intensities at the start represent at least 15 per cent of the total rainfall and the relatively low intensities that may follow the high intensities represent less than 15 per cent of the total rainfall. The relatively low intensities separating the high initial and final intensities in an interrupted storm represent at least 15 per cent of the total rainfall. The scattered intensities of a sporadic storm do not contain percentages of the total rainfall in positions to permit giving it another pattern-name.

Table 2 shows for the years 1937 through 1942 the number of storms in each class and pattern, the total rainfall for the storms in each pattern, and the distribution of some of the storms in selected months for each class. For example, in reference to distribution, the total number of

Table 2--Class, distribution, pattern, and total rainfall for 315 storms, 1937-42

Class	Total number of storms	Number of storms in selected months			Number of storms in each pattern			Number of storms in ranges of total rainfall, inches							
		Months	No.	Per cent	No.	Per cent	Pattern	0.25 to 0.50	0.51 to 0.75	0.76 to 1.00	1.01 to 1.25	1.26 to 1.50	1.51 to 1.75	1.76 to 2.00	2.01 to 2.25	2.26 and greater
I	36	Jan,Feb	17	47.2	36	100.0	Uniform	29	6	1	...	...	...	...	...	.....
		Jan,Feb, Nov,Dec	25	69.5			Sub-total, number	29	6	1	...	...	...	...	...	.....
							Per cent	80.5	16.7	2.8	...	...	...	...	...	.....
II	92	Jan,Feb,			17	18.5	Advanced	11	3	1	1	...	...	1	...	.....
		Mar,Apr	58	63.0	39	42.4	Intermediate	19	7	8	2	1	2	...	...	.....
		Jan,Feb,			20	21.7	Delayed	9	4	3	3	...	...	1	...	.....
		Mar,Apr,			8	8.7	Interrupted	1	1	1	1	1	1	1	1	.....
		Oct,Nov,			8	8.7	Sporadic	2	3	...	...	1	1	...	1	.....
		Dec	80	87.0			Sub-total, number	42	18	13	7	3	4	3	2	.....
							Per cent	45.7	19.6	14.1	7.5	3.3	4.3	3.3	2.2	.....
III	23	Oct	6	26.1	3	13.1	Advanced	1	1	...	...	1	...	...	...	.....
		Oct,Nov,			14	60.8	Intermediate	6	2	4	1	...	...	...	1	.....
		Dec	13	56.5	3	13.1	Delayed	1	1	...	...	...	...	1	...	.....
					1	4.3	Interrupted	...	1	...	...	...	...	...	...	.....
					2	8.7	Sporadic	1	...	...	1	...	...	...	...	.....
							Sub-total, number	9	5	4	2	1	...	1	1	.....
							Per cent	39.1	21.6	17.4	8.7	4.4	...	4.4	4.4	.....
IV	93	June,July,			50	53.8	Advanced	18	11	9	6	4	1	...	...	1 (3.42)
		Aug	51	54.8	29	31.2	Intermediate	6	6	11	2	1	2	1	...	.....
		May,June,			6	6.4	Delayed	2	2	1	...	...	1	...	...	.....
		July,Aug,			4	4.3	Interrupted	2	...	1	...	1	...	...	...	.....
		Sep	71	76.3	4	4.3	Sporadic	2	...	1	...	...	...	...	...	1 (2.68)
		Mar,Apr, May,June, July,Aug, Sep	84	90.3			Sub-total, number	30	19	23	8	6	4	1	...	2
							Per cent	32.3	20.4	24.7	8.6	6.4	4.3	1.1	...	2.2
V	71	June,July	44	62.0	7	9.8	Uniform	4	2	...	...	1	...	...	...	.....
		May,June,			40	56.3	Advanced	11	12	6	5	1	...	2	1	2 (2.50,
		July,Aug	64	90.2	6	8.5	Intermediate	2	...	1	1	...	...	...	2	2.70)
					9	12.7	Delayed	5	1	2	1	...	...	...	...	.....
					6	8.5	Interrupted	...	2	1	1	1	1	...	...	.....
					3	4.2	Sporadic	...	1	1	...	1	...	...	...	.....
							Sub-total, number	22	18	11	8	4	1	2	3	2
							Per cent	31.0	25.4	15.5	11.3	5.6	1.4	2.8	4.2	2.8
Total	315	.....						132	66	52	25	14	9	7	6	4
Per cent	100	.....						41.8	21.0	16.5	7.9	4.5	2.9	2.2	1.9	1.3

storms in the six-year period in Class I is 36, 17 or 47.2 per cent of which occurred in January and February and eight of which occurred in November and December, making a total of 25 (69.5 per cent) of the 36 occurring in January, February, November, and December. Figure 2 shows, for each class, the detailed distribution of storms in the different patterns. A definite seasonal distribution of classes and patterns is evident.

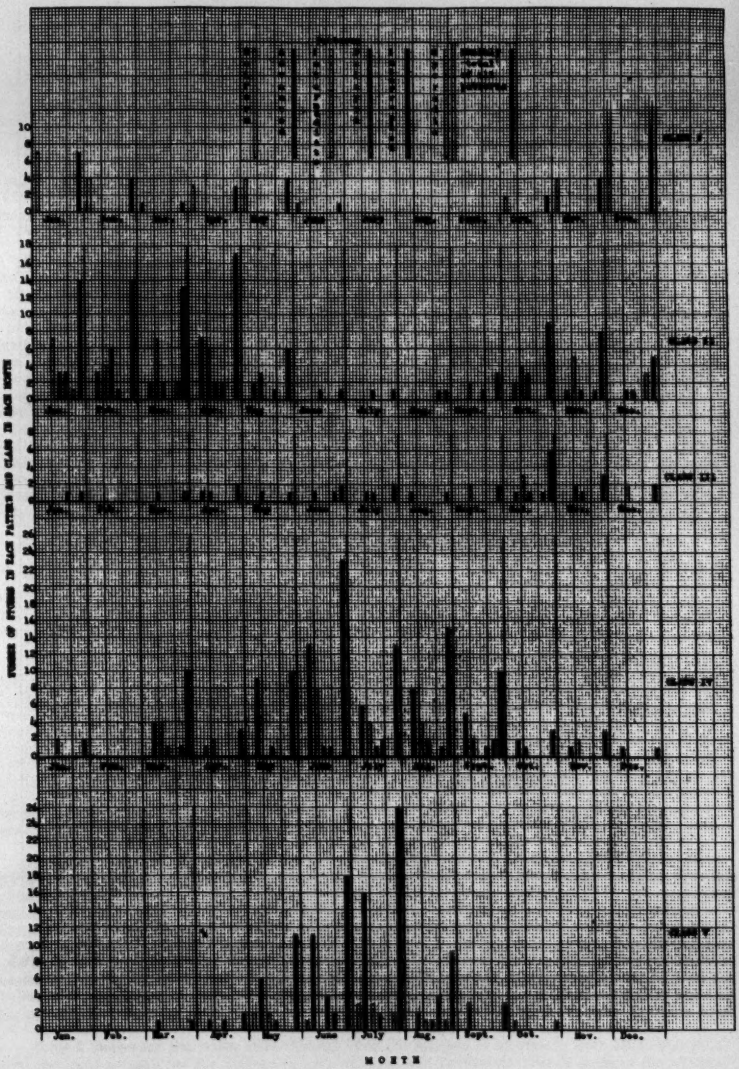

Fig. 2--Distribution of patterns in each month for storms occurring in Classes I, II, III, IV, and V during period 1937-1942

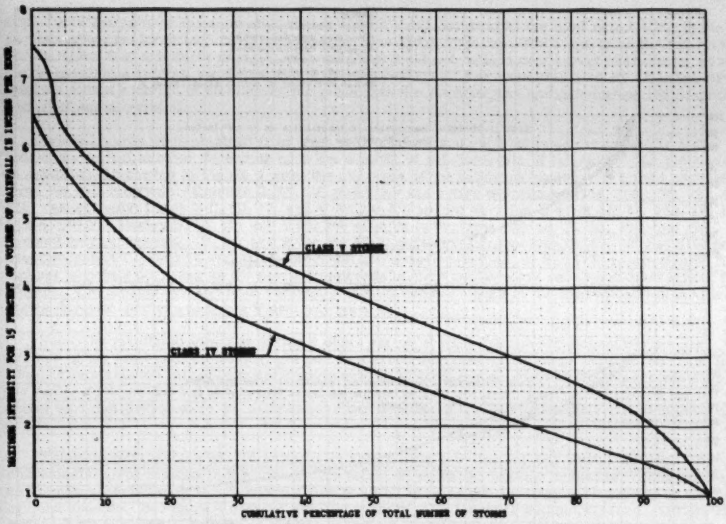

Fig. 3--Intensity of storms in Classes IV and V, 1937-1942

Variations in intensities within each class--In the foregoing a storm was placed in a given class because of its range in intensity and in a given pattern because of the sequence of its intensities. The detailed relationship of all intensities within each storm and selected portions of each storm is taken up in this section.

Extremes of variation in intensity for storms in Classes I, II, and III are established by definition. The maximum intensity for cumulative percentages of the total number of storms in Class IV and the total number of storms in Class V is shown in Figure 3. The maximum intensity as used in the preceding sentence was determined by averaging the highest intensities representing 15 per cent of the total rainfall for each storm.

BREIHAN [6] has shown that, on the average, half of the rainfall occurring within an hour actually falls at intensities equal to, or exceeding, twice the mean hourly rate. BLUMENSTOCK [7] has shown variations in mean intensity, from hour to hour, within storms of considerable duration.

The detailed relationship of precipitation-intensity within entire storms (usually of several hours' duration) and selected 60-, 40-, and 20-minute periods is shown in Figure 4 for 92, 23, 93, and 71 storms in Classes II, III, IV, and V, respectively. The 60-, 40-, and 20-minute periods were selected from the portion of each storm containing the highest intensities, except that isolated high intensities were not considered. Only one 60-, 40-, and 20-minute period was taken from each storm. Each period is continuous in time and was taken from that portion of the intensity bar-graph where the greatest amount of rain fell for the duration of that period, regardless of the position of the higher intensities within that period. The abscissa in Figure 4 is the ratio of the mean rainfall-intensity in a sub-interval of intensity (a sub-interval contains selected intensities from the intensity bar-graph) to the mean rate in an entire storm or a selected period, the duration of which is given by the legend at the top of the Figure. The first sub-interval contained only the highest intensity; the second sub-interval contained the highest intensity and the next lower intensity; each subsequent sub-interval included, in addition to the sub-interval preceding it, the next lower intensity. The number of sub-intervals obtained in a selected period of say 60 minutes was equal to the number of different intensities shown on the bar-graph for that period. The

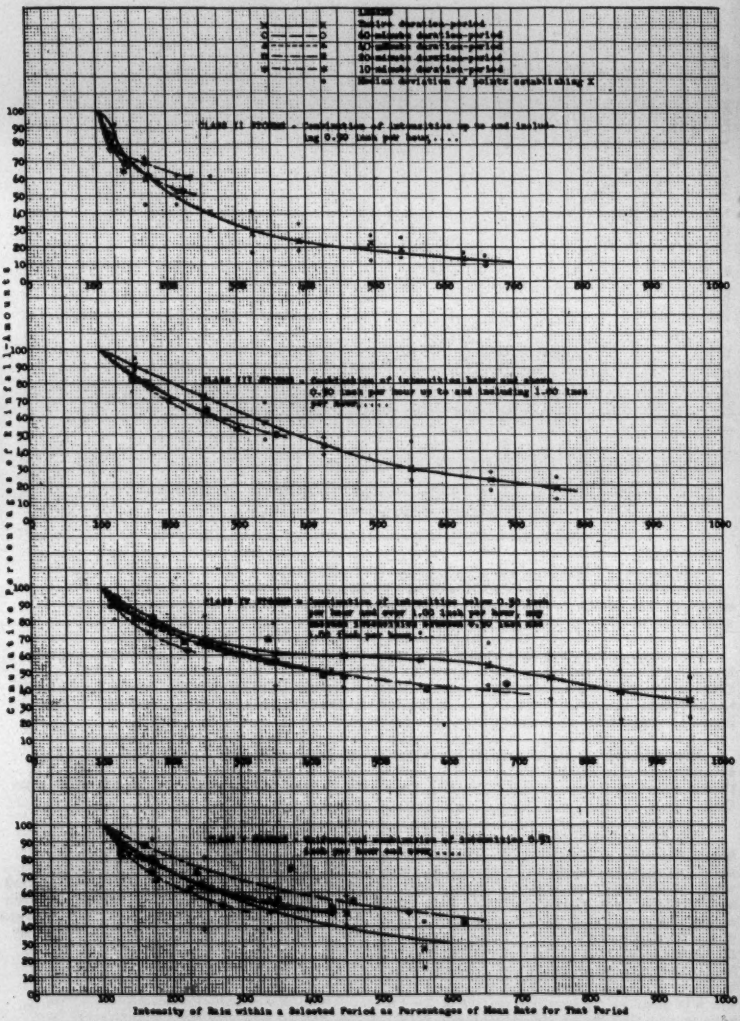
Cumulative Percentages of Rainfall Amounts
Intensity of Rain within a Selected Period as Percentages of Mean Rate for That Period

Fig. 4--Relationship of rainfall-intensity within each selected duration-period to mean rate for that period for storms in Classes II, III, IV, and V.

ordinate is the ratio of the amount of rain falling in a sub-interval to the total rain falling in the period under consideration. In determining the mean rate of rainfall for a storm or for any given period within that storm the duration of rainfall used did not include portions of time during which the intensities of rainfall were less than 0.01 inch per hour. For example, if no rain fell for six minutes within a period of 60 minutes the mean rate for the hour was computed using the 54-minute period of actual rainfall.

Several points were obtained from each entire storm and each selected period within that storm, the actual number depending upon the number of sub-intervals of intensity. The points used to establish the curves in Figure 4 were the averages of the following numbers of points obtained from the sub-intervals: Classes II, III, IV, and V for the entire duration-period, 300, 120, 420, and 215, respectively; Classes II, III, IV, and V for the 60-minute duration-period, 55, 45, 160, and 115, respectively; Classes II, III, IV, and V for the 40-minute duration-period, 35, 35, 155, and 155, respectively; Classes II, III, IV, and V for the 20-minute duration-period, 12, 13, 60, and 215, respectively; and Classes IV and V for the 10-minute duration-period, 30 and 115, respectively. The number of points decrease as the periods decrease in time as there are fewer sub-intervals of intensity. The median deviations of the points used to establish each of the average points for the entire duration-periods also are shown in Figure 4.

Since the maximum intensity within a short period of time represents a considerable percentage of the total rainfall for that period, the curves decrease in length as periods decrease in time. The maximum intensity represents generally at least ten per cent of the total rainfall for the entire duration-period and, consequently, the curves do not drop lower. The curves for the entire duration-period were not extended farther because of the scatter in the reduced number of points.

Establishment of classes and patterns of rainfall for selected periods within storms--The characteristics of rainfall in the portion of a storm in which the highest intensities occur, as well as the characteristics of entire storms, are believed to be important from a standpoint of hydrology and erosion. In Figure 4 detailed relationships of all intensities within Classes II, III, IV, and V are shown but not the number of storms occurring in each class and their pattern.

This section is devoted to a classification of the rainfall for 60-, 40-, and 20-minute periods taken from the portion of each of the storms, in Table 1, containing the highest intensities. The periods were selected in the same manner as they were under the section on "Variations in intensities within each class". The total number of 60-, 40-, and 20-minute periods investigated were 285, 289, and 296, respectively. Since storms of Class I were included here these numbers are greater than those used to obtain Figure 4. These numbers are somewhat less than the 315 storms available because periods containing gaps of no rainfall for more than five minutes were discarded.

Table 3 shows the class and pattern of the selected periods within the storms investigated. Figure 5 shows, for each class and pattern, the detailed distribution of the 60-minute periods.

In general, in comparing Figure 5 with Figure 2 the number in Class I is considerably higher (many storms in Class II change to I), in Class II considerably less, in Class III about the same, in Class IV somewhat less, and in Class V the same (higher for the 40- and 20-minute periods as a number of storms in Class IV change to Class V).

Classes I and II for the 60-, 40-, and 20-minute periods appear chiefly in the winter and early spring. Class III is fairly well distributed throughout the seasons. Class IV and V occur in the late spring and summer. Class V is the most definite summer type.

Duration of storms and maximum intensity--Table 4, for the years 1937 through 1942, shows: (1) The average time from the start of storms to the maximum intensity in the advanced, intermediate, and delayed patterns of Classes II, III, IV, and V; (2) the range in the duration of the maximum intensities and the average duration of the maximum intensities for all of the storms in each pattern; (3) the average duration of all storms in each pattern in the various ranges of rainfall. Rather definite trends are apparent.

Use of classes and patterns of rainfall--The interpretation of the effect of rainfall-intensities and their pattern upon the hydrologic performance of watersheds under different conditions and in different land-use is a major hydrologic problem. The pattern and class of rainfall, in representing the occurrence of various intensities, when related to the infiltration-rate, determine the rainfall-excess or the supply available for surface-runoff. It is not intended to imply that knowledge

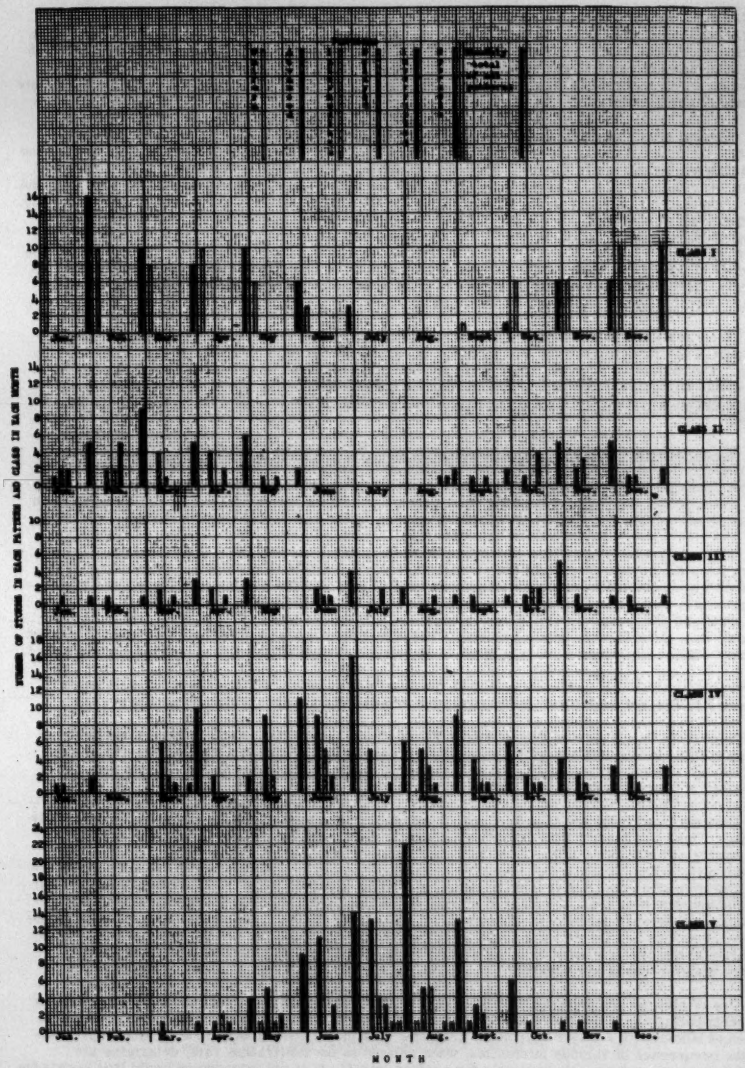

Fig. 5--Distribution of patterns in each month for selected 60-minute periods within storms occurring in Classes I, II, III, IV, and V during 1937-1942

Table 3--Class and pattern of selected periods within 315 storms, 1937-42

Class	Number of selected periods in each pattern								
	60-minute			40-minute			20-minute		
	Number	Per cent	Pattern	Number	Per cent	Pattern	Number	Per cent	Pattern
I	76	100	U	87	100	U	104	100	U
II	17	39.5	A	12	38.7	A	12	70.5	A
	9	20.9	I	5	16.2	I	1	5.9	I
	15	35.0	D	13	41.9	D	4	23.6	D
	1	2.3	T	1	3.2	T	0	0	T
	1	2.3	S	0	0	S	0	0	S
	43	100	...	31	100	...	17	100	...
III	11	47.8	A	10	50	A	8	57.1	A
	5	21.8	I	4	20	I	2	14.3	I
	7	30.4	D	6	30	D	4	28.6	D
	0	0	T	0	0	T	0	0	T
	0	0	S	0	0	S	0	0	S
	23	100	...	20	100	...	14	100	...
IV	47	65.3	A	38	57.6	A	27	58.7	A
	17	23.6	I	17	25.8	I	9	19.6	I
	6	8.3	D	8	12.1	D	10	21.7	D
	1	1.4	T	2	3.0	T	0	0	T
	1	1.4	S	1	1.5	S	0	0	S
	72	100	...	66	100	...	46	100	...
V	3	4.2	U	7	8.2	U	20	17.4	U
	41	57.7	A	49	57.6	A	64	55.6	A
	14	19.8	I	13	15.3	I	11	9.6	I
	9	12.7	D	13	15.3	D	18	15.7	D
	2	2.8	T	2	2.4	T	0	0	T
	2	2.8	S	1	1.2	S	2	1.7	S
	71	100	...	85	100	...	115	100	...
Grand total	285	.....	...	289	.....	...	296	.....	...

of the seasonal characteristics of rainfall is sufficient in itself to determine surface-runoff. As pointed out in the beginning of this paper the hydrologic performance of a watershed is also dependent upon the conditions of watershed, which are also dependent upon rainfall-characteristics. However, as information pertaining to conditions of watershed develops the interpretation of the effect of rainfall-characteristics will advance, particularly as watershed-performance is associated with both conditions of watershed and characteristics of rainfall.

The writer has studied numerous hydrographs, including many analyzed and discussed by such investigators as HORNER [8,9]. This study indicates that infiltration-capacity and surface-runoff vary materially with the intensity and pattern of rainfall and immediately antecedent conditions. HORNER and JENS [5] have shown that the sequence of intensities have considerable influence on surface-runoff.

Each example in Figure 6 shows that different rainfall-patterns for two storms producing about the same total precipitation in about the same time resulted in different infiltration-curves on the same watershed when in approximately the same condition. The determination of the infiltration-curves was based on methods by HORNER [8,9] and SHARP and HOLTAN [10], and as modified by the author. A symbolized storm-description accompanies each infiltration-curve. For example, in Figure 6-A under Storm II is $^{0.93}1.03\ h\ V_{3.17}^{I}$, which describes the storm as follows: 0.93 is the total amount of rainfall in inches, 1.03 h is the duration of actual rainfall in hours (only includes sub-intervals in which the intensities are 0.01 inch per hour or more), V is the class, 3.17 is the maximum average intensity in inches per hour for 15 per cent of the total rainfall (in this case the average intensity of the sub-intervals 4.20 and 3.0), and I represents the intermediate pattern.

Table 4--Time from start of storm to maximum intensity and duration of maximum intensity and storms, 1937-42

Class	Total number of storms	Pattern	Average time from start of storm to maximum intensity[1]	Duration of maximum intensity[2]			Average duration[1] of storms in each pattern and class for various ranges of total rainfall[3]								
				Range		Average	0.25 to 0.50	0.51 to 0.75	0.76 to 1.00	1.01 to 1.25	1.26 to 1.50	1.51 to 1.75	1.76 to 2.00	2.01 to 2.25	2.26 and greater
			h m	From m	To m	m	h	h	h	h	h	h	h	h	h
I	36	Uniform	.. ...	...	...	...	6.6	15.1	16.0	.....	.....	.....	.....	.....	.....
II	92	Advanced	0 18	4	66	30	4.6	8.7	14.2	8.7	.....	.....	14.6	.....	.....
		Intermediate	2 02	6	75	39	5.0	9.3	10.6	12.6	9.7	15.3	.....	.....	.....
		Delayed	5 48	7	60	37	4.3	8.6	10.5	12.2	.....	.....	13.1	.....	.....
		Interrupted	.. ...	2	68	23	1.0	8.0	10.7	13.3	11.6	10.0	15.2	30.4	.....
		Sporadic	.. ...	10	72	36	6.2	12.4	.....	.....	13.7	12.7	.....	20.0	.....
		Average[1]	... ...	2	75	35	4.7	9.5	10.9	12.0	11.7	13.3	14.3	25.2	.....
III	23	Advanced	0 33	7	17	10	1.5	4.8	.....	.....	14.8	.....	.....	.....	.....
		Intermediate	1 39	8	40	18	4.0	7.2	9.9	5.6	.....	.....	.....	18.0	.....
		Delayed	5 42	8	27	14	7.6	7.3	.....	.....	.....	.....	11.4	.....	.....
		Interrupted	.. ...	...	...	...	....	4.0	.....	.....	.....	.....	.....	.....	.....
		Sporadic	.. ...	7	21	12	4.0	.....	.....	5.5	.....	.....	.....	.....	.....
		Average[1]	.. ...	6	40	15	4.1	6.1	9.9	5.6	14.8	.....	11.4	18.0	.....
IV	93	Advanced	0 05	2	8	6	1.5	2.7	2.8	4.6	9.1	2.4	.....	.....	16.6
		Intermediate	1 39	1	10	6	1.9	5.1	6.4	3.7	7.4	10.5	11.3	.....	.....
		Delayed	3 06	3	12	5	0.2	4.8	4.5	.....	.....	10.7	.....	.....	.....
		Interrupted	.. ...	3	14	5	1.1	.....	0.9	.....	5.6	.....	.....	.....	.....
		Sporadic	.. ...	2	10	3	4.5	.....	1.6	.....	.....	.....	.....	.....	17.0
		Average[1]	.. ...	2	14	6	1.7	3.7	4.5	4.4	8.2	8.5	11.3	.....	16.8
V	71	Uniform	.. ...	...	...	...	0.2	0.6	.....	.....	0.4	.....	.....	.....	.....
		Advanced	0 04	2	11	6	0.4	0.9	0.6	0.9	3.9	.....	3.2	6.9	5.9
		Intermediate	0 10	2	14	11	0.5	.....	0.9	1.0	.....	.....	.....	5.5	.....
		Delayed	0 12	1	9	5	0.3	1.5	0.4	1.4	.....	.....	.....	.....	.....
		Interrupted	.. ...	2	8	7	....	1.3	1.5	1.0	3.7	2.5	.....	.....	.....
		Sporadic	.. ...	2	4	6	....	1.0	1.0	.....	0.7	.....	.....	.....	.....
		Average[1]	.. ...	1	14	6	0.4	0.9	0.7	1.0	2.2	2.5	3.2	6.0	5.9

[1] Average determined from all the storms in a given pattern or class (see Table 2).
[2] Maximum intensity represents 15 per cent of the total rainfall for each storm.
[3] See Table 2 for number of storms in each pattern and range.

Some information on the conditions of vegetal cover and soil immediately prior to each storm are also noted. However, these do not describe such considerations as the soil-surface conditions or the location of soil-moisture. Differences in the infiltration-curve are due probably to one or more of three causal factors: (1) The rainfall-pattern; (2) changing watershed-conditions during a storm; and (3) difference in antecedent watershed-conditions (includes antecedent rainfall-amounts in some cases).

In each example in Figure 6 it is believed that the pattern of rainfall was primarily responsible for the fact that the rate and amount of runoff in Storm II are almost as great or greater than in Storm I, even though the intensities of rainfall are lower. The effect of antecedent rainfall and runoff on such conditions of watershed as sealing and soil-moisture is estimated to be about the

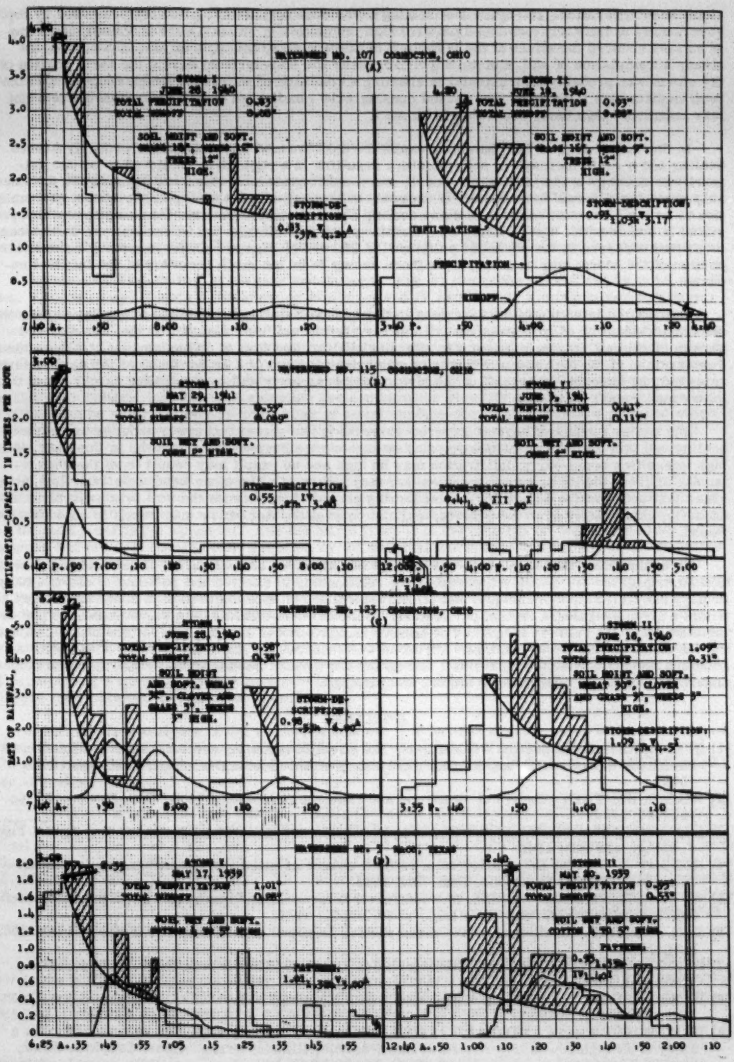

Fig. 6--Infiltration-curves

same in each example. In Figure 6-A sealing of the soil-surface was probably prevented by the cover, most of the early (advanced pattern) high intensities in Storm I were absorbed, and a gap of no rain reduced the effect of the last block of fairly high intensity; whereas, in Storm II, the steady accumulation of soil-moisture (probably near the soil-surface) during the early portion of the storm was probably instrumental in creating a condition of watershed which responded to the intermediate high intensities that caused considerable runoff even though the intensities were of less magnitude than those occurring in Storm I.

In Storm I of each of the remaining examples the advanced high intensities probably caused sealing and a rapid increase in soil-moisture resulting in a rapid drop (believed to be due primarily to sealing) in the infiltration-curve, and if subsequent intensities had been higher considerably more runoff would have resulted; whereas, in Storm II of each example, the steady accumulation of soil-moisture in addition to some sealing seems to be responsible for conditions which resulted in considerable runoff under intermediate patterns, although the intensities are lower than those that occurred in the advanced patterns. In Storm I of Figure 6-C the records for the latter portion of the storm may be in error as there seems to be too much recovery of the infiltration-curve.

It is not the intention in the foregoing to discuss the relative importance of sealing versus the amount and location of soil-moisture. It has been fairly well established that the intensity and pattern of rainfall may be important in affecting sealing, and thus in influencing infiltration-rates. For example, if the high rates of intensity occur near the end of a storm much of the earlier lower rates may be absorbed; whereas, if the high rates occur early and cause sealing, lower rates that follow may appear as runoff.

The writer's study of vegetal-covered watersheds has shown that cover reduces or prevents sealing and that the rate of infiltration may be high over a considerable period. In this case, if high intensities occur early, infiltration may be high and no runoff may result from the high intensity or from the lower intensity-rates that may follow. On the other hand, relatively low intensities that occur at the outset for a considerable period of time cause the soil to approach its field-capacity, particularly near the surface, and high intensities that follow may result in considerable runoff.

To summarize, the writer believes that the use of such a classification of rainfall as presented will be helpful to: (1) The development of the relationship of classes and patterns of storms to hydrology and infiltration-technique; and (2) the application of hydrologic data to some localities within a given hydrologic region, particularly where detailed rainfall-data do not exist, for the determination of the relative frequency of classes and patterns of storms, the pattern of rainfall during the seasons, and the approximate variation in intensities for different classes of storms. A standard method of classifying rainfall throughout the country should prove helpful to a common understanding of one of the major factors in hydrology.

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DISCUSSION

A. L. SHANDS (U. S. Weather Bureau, Washington, D. C.)--This paper renews the proper emphasis that has been placed in recent years on the variation of intensities within the rain-period and on the inadequacy of representing the rainfall by a mean rate. The author establishes five classes of storms based on the magnitude of intensities and adds two groups to the classification by pattern or sequence of intensities suggested by HORNER and JENS [5 of author's references].

The monthly distribution of classes and patterns (Fig. 2) shows the classification to be significant. Classes I and II show a midsummer minimum and IV and V show a midsummer maximum. Class III seems to be a transition-group that shows no marked fluctuation in monthly frequency. What this means, of course, is something already known--that in a region like Ohio, the higher intensities will in general occur in midsummer. It is of interest, too, that while the uniform and intermediate patterns predominate in the lower-intensity groups, the advanced pattern is predominant in the higher. This agrees with meteorological experience, the general cause being the greater atmospheric instability of summer, the comparative stability of winter. The highest intensities can be achieved only by convection of moist surface-air to high levels, a process which exceeds in rapidity the comparatively gradual lifting of air along a frontal surface. As is well known, convection is more characteristic of the summer and frontal movements of the winter.

It should be of interest to identify some of the patterns, if not the magnitudes, with typical fronts. In the storm-studies made by the Hydrometeorological Section of the Weather Bureau, it has been found that on the average a front produces a typical mass-curve of rainfall. The pattern for the cold front is the advanced. For the warm front it is the uniform or the intermediate. The patterns are not only theoretically justified by the comparative slopes and velocities of the fronts but verified by the automatic rainfall-records. However, there are enough variations from the average pattern to justify an analysis like Mr. Schiff's. A retardation of the cold front will modify its typical rainfall-pattern in the direction of uniformity, while the achievement of convective instability [C.-G. ROSSBY, Thermodynamics applied to air mass analysis, Mass. Inst. Tech. Met. Papers, v. 1, No. 3, 1932] in layers of air being lifted up the warm-front surface will produce variations of intensity that may fit any of the patterns, depending on the spacing of the outbursts. The quasi-stationary front characteristic of some Ohio synoptic situations could also produce a series of outbursts at a station--and the pattern-classification would depend entirely on the length of elapsed time between measurable rains.

In Mr. Schiff's analysis of the Coshocton storms it is notable that the rates become more and more uniform as the rainfall-periods considered for classification by magnitude are shortened. The total number of shorter periods within each classification derived from Mr. Schiff's figures are as follows:

Period	Number in each Class				
	I	II	III	IV	V
Total	36	43	23	93	71
60-minute	76	43	23	76	71
40-minute	86	31	20	66	85
20-minute	104	17	14	46	115

Only Classes I and V include uniform intensities, although the latter may also include a combination of intensities higher than 0.50 inch per hour. Figure 4 shows that, for the 60-minute period, uniformity in Class V is actually less frequent than in the total storm. It should also be remembered that these periods were taken from the portions of the storms containing the highest intensities and periods containing gaps of no rainfall were discarded.

The point to be made is that the Class (of intensity-magnitude) is not independent of duration, nor is the pattern. This is not to say that the author overlooks this fact although his classification excludes it. In comparing the intensity-infiltration-runoff patterns of two storms he finds it necessary to identify the storms by a code which includes both total rainfall and duration.

In evaluating Mr. Schiff's results it is important, also, to realize that his is essentially an analysis of point-rainfall. The record by which any storm is classified in his procedure is the "representative" record of the station at the storm-center (meaning isohyetal center) and there-

fore usually the station having the greatest catch. The station is therefore not representative of the average depth unless we assume a watershed so small that the record at a single station can be considered to apply uniformly throughout the area. The patterns or sequences of intensities, however, are likely to be the same throughout a large area, if the rainfall is homogeneous in the sense of being assignable to the same meteorological incident such as a thunder-storm or frontal passage. Of cqurse, in the outer portions of the storm-area the peak-intensities would be so modified that the overall pattern for outlying stations would emerge as uniform or sporadic.

A simple way of combining intensities varying over an area has not been found nor, perhaps, is there any simple way. HORNER [8 of author's references] has previously shown how the use of averaged intensities would falsify the rainfall-runoff relationship since what has to be contended with quite often is partial-area runoff. It is possible that Mr. Schiff's classification is accurate for the small area he has considered (although the choice of the station with the greatest rainfall-amount makes it doubtful) but the adaptation to larger areas must involve the subdivision of the areas into units (for example, Thiessen blocks) for which the intensity-range and pattern at a particular station can be considered applicable.

THE RELATION OF RAINDROP-SIZE TO INTENSITY

J. Otis Laws and Donald A. Parsons

Introduction--Curiosity concerning the drop-size composition of natural rain has arisen from attempts to measure erodibility and infiltration-capacity by sprinkling small areas of land with artificial rain. The results have been found to be affected by the drop-size and velocity of the artificial rains applied, and the applicability of such results to conditions of natural rainfall has been thrown in doubt.

To aid in the design of rain-simulators, this survey of raindrop-sizes was initiated by technicians [D. A. PARSONS, J. O. LAWS, and Senior Scientific Aide S. R. KLINE under the leadership of H. L. COOK, Head of the Hydraulic Section] of the Soil Conservation Service working on this problem at the Hydraulic Laboratory, National Bureau of Standards, Washington, D. C., and samples were collected on the roof of that Laboratory during 1938 and 1939. Measurements of drop-velocities after limited heights of fall were also made and these have been reported [see 6 of "References" at end of paper]. Studies of the relation of drop-size and velocity to erosion and infiltration were also begun and are now being continued at Auburn, Alabama. A brief description of these studies was published in 1940 [5].

It is hoped that these drop-size measurements will prove useful in the evaluation of simulated-rain tests and in the interpretation of phenomena of erosion generally.

Review of literature--Raindrop-sizes were first measured in Germany about 1895. J. WIESNER [9] pioneered in this field and published a description of his absorbent-paper method of measuring drop-size.

This method, with slight modifications, has been used by all subsequent European investigators and consists of exposing sheets of filter-paper, dusted with a water-soluble dye, to the rain for a brief interval. Upon striking the paper, the drops cause spots that are rendered permanent by the dye. To find the radius of the drop, r, that produces a spot of radius R, the effective thickness of the paper must be known. This is found by equating the volume of the spherical drop $[(4/3)\pi r^3]$, to the volume of the flat disc of wetted stain of volume $(\pi R^2 h)$, and solving for h to obtain $h = (4/3)(r^3/R^2)$. ALBERT DEFANT [3] showed that the factor h, which might be expected to be a constant for a given paper, varied markedly with drop-size. A. BECKER [1] reexamined Defant's measurements in 1907 and found that the factor also varied with drop-velocity. The control of the humidity in the paper-storage was also found necessary.

The large drops spatter upon striking the paper and the precise determination of their size is not possible. NIEDERDORFER [8] estimates an average error ranging from 14 per cent of the drop-weight at 0.037 mgm to six per cent for a drop-weight of 37 mgm.

Wiesner's interest lay primarily in the largest drops and he went to some pains to refute the then popular notion that the drops of tropical rains were sometimes an inch in diameter.

P. LENARD [7] was the first investigator to show an interest in the frequency-distribution of raindrop-sizes and, in 1904, he published tabulations showing the frequency of occurrence of drops

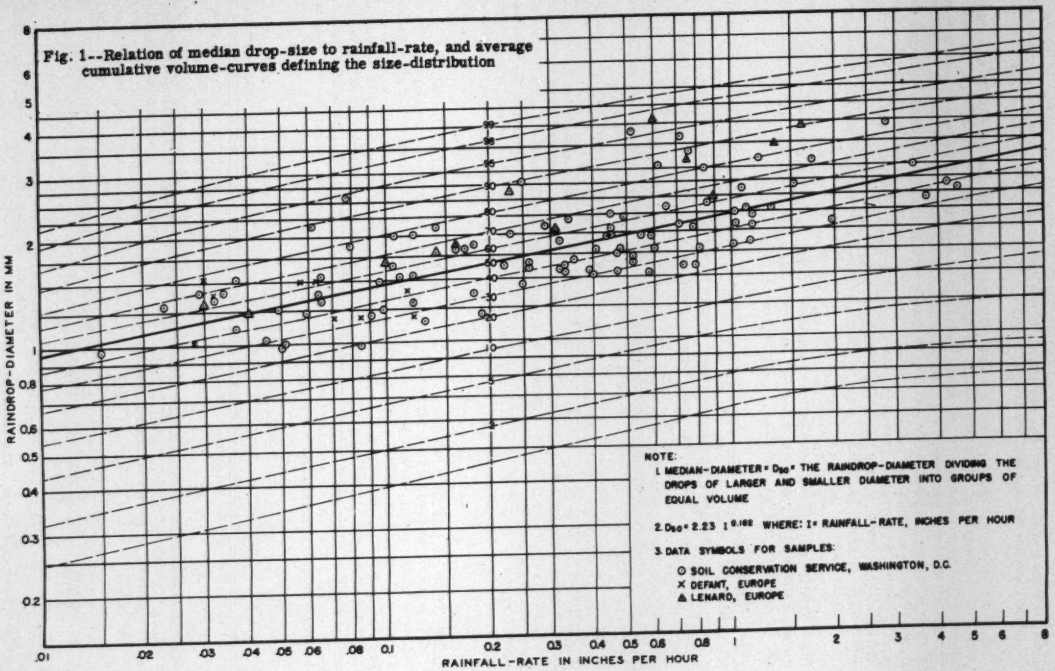
RAINDROP-DIAMETER IN MM
RAINFALL-RATE IN INCHES PER HOUR
NOTE:
1. MEDIAN-DIAMETER = D_{50} = THE RAINDROP-DIAMETER DIVIDING THE DROPS OF LARGER AND SMALLER DIAMETER INTO GROUPS OF EQUAL VOLUME
2. $D_{50} = 2.23\ I^{0.182}$ WHERE: I = RAINFALL-RATE, INCHES PER HOUR
3. DATA SYMBOLS FOR SAMPLES:
⊙ SOIL CONSERVATION SERVICE, WASHINGTON, D.C.
× DEFANT, EUROPE
△ LENARD, EUROPE

Fig. 1--Relation of median drop-size to rainfall-rate, and average cumulative volume-curves defining the size-distribution

of different sizes in several rains. His tabulations of the number of drops per square meter per second have been converted into median drop-size and intensity and are presented in Figure 1.

A year after the appearance of Lenard's work, DEFANT [3] published the results of a painstaking study of raindrop-size. His measurements were more precise and revealed a decided waviness in the frequency-size curve, the most frequently occurring drops having volumes in the ratios of 1:2:4:8. This curious result stimulated discussions that have continued until the present day [10]. Defant reported the total number of drops in 29 size-groups for 20 rains, and again the total number of drops in 26 size-groups for seven rains. His smallest group included all drops less than 0.024 mgm (0.36 mm) and in his largest group he lumped all drops over 5.25 mgm (2.16 mm). The upper limit of drop-size is not reported, and in several of the rains a sufficient number of drops fell in the largest group to indicate that drops over 5.25 mgm contributed a considerable part of the total volume.

In converting Defant's data for inclusion in Figure 1, it was assumed that the mass of the average drop in the largest group was ten mgm, and when the number of drops in this group was over five, a conversion was not risked.

In 1932 E. NIEDERDORFER [8] reopened the question of size-ratios in raindrops by publishing an exhaustive analysis of eight rains in which he divided the drops into no less than 97 size-groups. These measurements confirmed and amplified Defant's observations. Unfortunately, Niederdorfer reported no rainfall-rates, so it was not possible to include his data in Figure 1.

WILSON A. BENTLEY [2] is the only American investigator who has reported measurements of drop-size. This meteorologist did his brief work in this field without reference to the German investigators and employed an ingenious method of measurement which has been adopted with modifications in making the measurements reported here. Bentley's measurements were not extensive.

W. J. HUMPHREYS [4] presents a table in which he lists, among other things, intensity and drop-size in parallel columns. No sources are quoted, but the data are believed to have been derived from Lenard and Defant [3,7]. The manner of deriving the "drop-diameter", which is evidently some sort of an average, is not described, and a valid comparison with the relation between median drop-size, as defined in this paper, and intensity is not possible. Neglecting this important difference, Humphreys' values appear too low at the low intensities and too high at the high intensities.

The flour-method of size-measurement--As described by BENTLEY [2], this method is as follows: "The method employed was to allow the raindrop to fall into a layer one inch deep of fine, uncompacted flour, with a smooth surface, contained in a shallow tin receptacle about four inches in diameter, which was generally exposed to the rain for about four seconds, although a longer time was given when the drops fell scatteringly. The raindrops were allowed to remain in the flour until the dough-pellet that each drop always produces . . . . . was dry and hard. These dough-pellets, which were found by careful experiment to correspond very closely in size with the raindrops that made them, were then extracted, labeled, and photographed, or kept on file for reference, together with the attendant meteorological data . . . ."

In adapting this method, it was found convenient to separate the dried pellets by means of a set of standard sieves into groups of several sizes. This technique shortened the labor of sorting drop-sizes and made feasible a more thorough survey. The catches on the various sieves were weighed, just as is done in the mechanical analysis of a sediment. The limits of drop-size, however, cannot be found from the dimensions of the sieve-openings because of the flattening the drop undergoes in becoming a pellet. Lacking well-determined limits of size, the mass of the average pellet was used to typify a separation, this average being found by dividing the mass of the separate by the number of pellets composing it.

Table 1--Mass of flour pellet

Sieve-numbers	Mass of average pellet	Standard deviation of single observation	
	mgm	mgm	pct
10-14	2.08	0.34	16
14-20	0.786	0.10	13
20-28	0.280	0.028	10
28-35	0.107	0.0085	8

As might be expected, the mass of the average pellet passing a given sieve and retained on another is more or less constant from one rain-sample to the next. The constancy of this value was studied with the results in Table 1. Fortunately, the average is fairly constant for the smaller separations where counting becomes tedious.

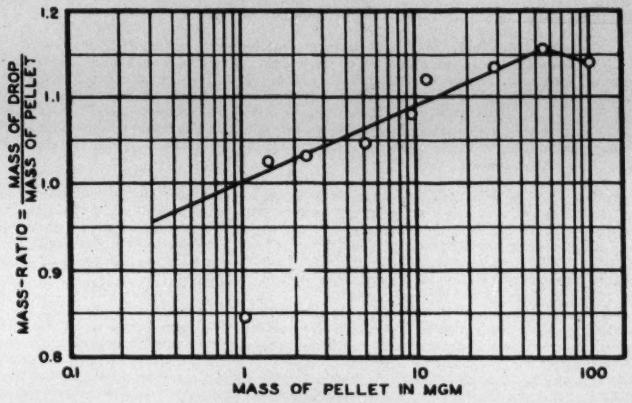

Fig. 2 --Flour-calibration

In the analysis of the samples in this survey, estimates of the mass of the average pellet were made only in the two smallest separations for the last 26 samples analyzed.

To convert the mass of the average pellet into the mass of the average drop, it is necessary, of course, to know the ratio of the mass of the drop to the mass of the pellet. For brevity, this will be referred to as the "mass-ratio."

To determine this mass-ratio, the general technique of previous investigators was followed. Drops of known sizes were produced by allowing water to drip from tubes of various diameters. When water was dripping at a constant rate, a counted number of drops was collected in a weighing bottle that was immediately covered and weighed. The collection of drops was repeated several times to make sure the drop-size was constant, and finally a number of drops were allowed to fall into a pan of freshly sifted and smoothed flour. Afterward a check-measurement was often made of the drop-size by catching more drops and weighing.

The waterdrops in the flour were then allowed to dry, and the hard pellets thus produced were separated from the flour by sieving through a 70-mesh sieve. A sieve 20 inches in diameter was constructed for this purpose. To standardize conditions under which these and subsequent rain-sample pellets would be dried, the air-dry pellets were redried in an oven at 110°C for 60 minutes. (Two hours would have been a better drying time because the pellets were still losing moisture at a fairly rapid rate.) All pellets were then weighed together and their average mass computed.

The ratio of the mass of the drop to the mass of the pellet was then computed. Like the effective thickness of the absorbent paper, this ratio might be expected to be constant. Unfortunately, it varies with size as is shown in Figure 2. In this Figure the mass of the pellet has been plotted along a logarithmic scale in order to spread out the data.

It will be observed that no values below a pellet-mass of 1.035 mgm (drop-mass of 0.877 mgm) were obtained. Since many raindrops are smaller than this, it would be highly desirable to extend the calibration to lower values, but the production of drops as small as 0.877 mgm is very difficult. Hair-like capillaries must be used; these must be coated with paraffin; pressure must be used to hasten dripping; and every precaution must be taken to keep trash out of the water, because the capillaries readily become clogged.

In drawing the curve through the points of Figure 2, the 1.035-mgm value has been disregarded. It is the writers' opinion that the determination was in error. Although repeated attempts were made to verify this value, drops this small could not again be produced. NIEDERDORFER,

on the other hand, reports producing drops as small as 0.99 mm (0.5 mgm).

In the subsequent analysis of rain-samples, values for the mass-ratio were never taken less than unity, even though an extrapolation of the curve of Figure 2 would indicate values as low as 0.9 for the smallest separates. This resulted from the use of a calibration-curve drawn on arithmetically-ruled paper, and it was not considered serious enough to correct.

The uncertainty surrounding the very small drops is an unavoidable shortcoming of not only the flour-method, but also the absorbent-paper method. Fortunately, drops of this size contribute relatively small volumes of rain.

Sampling procedure--Samples were taken in pans of flour ten inches in diameter and one inch deep, and these were exposed for intervals ranging from a few minutes to a fraction of a second, depending upon the rain-intensity. The pans were exposed in rapid succession during periods of high rainfall-rate and at intervals of a half hour or so during low-intensity periods. An endeavor was made to take á sample with each 0.05 inch of rainfall, but the portions of the rain falling in the early morning and on holidays were often missed completely.

To collect a sample, the observer sifted calibrated flour into the pans and scraped off the excess flour so as to leave a smooth, uncompacted surface. Prepared pans were not allowed to stand for more than two hours without resifting. The observer placed the pan on the palm of one hand and, shielding the flour with a large cover held in the other hand, stepped out on the flat roof of the laboratory. The cover was then snatched away while the pan was held well away from the body so that the sample would not be contaminated with splashes from the observer's hat. When the flour was moderately sprinkled, the cover was replaced. A record was made of the duration of exposure and the hour and minute of the day.

A Fergusson-type weighing rain-gage was located on this roof and its clock was synchronized with the observer's watch.

Sorting procedure--After allowing the raindrops to dry in contact with the flour overnight, the hard, dry pellets were screened out by emptying the entire contents of the flour pan into a large 70-mesh sieve. When most of the flour had been shaken and beaten through the sieve, the pellets and remaining flour were transferred to evaporating dishes and heated in an oven at 110°C for 60 minutes. The pellets were next introduced into the top of a stack of sieves--numbers 8, 10, 14, 20, 28, and 35. The stack of sieves were then shaken for about two minutes on a sieve-shaking machine. The catches on the several sieves were then counted and culled. Culling consisted of removing foreign matter and double pellets formed by two drops falling too closely together. The catch of each sieve was weighed on an analytical balance to 0.1 mgm. Effects of humidity on the weight of the pellets were not appreciable.

Determination of median drop-size--The method of analyzing individual samples is illustrated in Table 2. The method of obtaining the "Cumulative volume" was difficult to indicate in the Table. The values entered represent the per cent of the total volume of the sample contributed by drops smaller than the corresponding average drop. In deriving these values, half of the volume of a separate was assumed to have been contributed by drops smaller than the average. Thus the cumulative volume for the last separate is (5.4/2) = 2.7 per cent. Since mass is proportional to volume, per cent of total volume is equal to per cent of total mass. The cumulative volume for the fifth separate is [5.4 + (10.8/2)] = 10.8 per cent. For the fourth separate it is [5.4 + 10.8 + (22.4/2)] = 27.4 per cent. And so forth.

The cumulative volume was then plotted against the diameter of the average drop and gave a typical cumulative-frequency curve, or "ogive" as it is often called. Frequency in this case is based upon volume rather than number and, to avoid confusion, such diagrams will be referred to as cumulative-volume curves with the understanding that the volume is expressed as per cent of total sample volume. To save space, examples of these curves have been omitted.

The median drop-size is determined by the intersection of the cumulative-volume curves with the 50 per cent line. The median drop-diameter is defined as the abscissa of the point on the cumulative-volume curve having an ordinate of 50 per cent. So defined, the median drop divides the larger and smaller drops of the sample into two groups of equal volume.

Determination of size-distribution--To determine the relation of size-distribution to rainfall-rate, the samples were arranged in order of intensity and, since samples of nearly equal intensity displayed wide differences in distribution, they were divided into groups of ten. Cumulative-volume

Table 2--An illustrative computation for a single rain-sample

[Rain of July 21, 1938; pan 3; time $9^h\ 53^m$ a.m. (July 22, 1938); pan-exposure 4.8 sec; rain-sample 35]

Sieves	Mass of all pellets, M_p	Number of pellets, n	Mass of average pellet, $m_p = (M_p/n)$	Mass-ratio, R	Mass of all drops, $M = R M_p$	Mass of average drop, $m = R m_p$	Diameter of average drop, $d = \sqrt[3]{(6/\pi)m}$	Per cent of total mass, $100 M/\Sigma M$	Cumulative volume
	mgm		mgm		mgm	mgm	mm	pct	pct
7 - 8	19.1	2	9.55	1.08	20.6	10.3	2.70	2.2	98.9
8 - 10	197.1	44	4.48	1.06	209.0	4.75	2.09	22.2	87.7
10 - 14	339.0	159	2.13	1.03	349.0	2.19	1.61	37.0	57.1
14 - 20	211.5	385	0.55	1.00[a]	211.5	0.55	1.015	22.4	27.4
20 - 28	101.6	354	0.287	1.00[a]	101.6	0.287	0.818	10.8	10.8
28 - 35	50.5	460	0.110	1.00[a]	50.5	0.110	0.594	5.4	2.7
ΣM = mass of all drops in sample		.....			942.2	.....	.....	.....	.....

Rainfall-rate = volume of all drops in sample divided by product of pan-area and pan-exposure = $(942.2/25.4^3)/(\pi 5^2)(4.8/3600) = 0.55$ inch/hr

[a]These ratios are below the limit of calibration.

Table 3--Size-distribution of raindrops, per cent of total volume

Drop-diameter limits	Rainfall-rate in inch/hour							
	0.01	0.05	0.1	0.5	1.0	2.0	4.0	6.0
mm mm								
0.00 - 0.25	1.0	0.5	0.3	0.1	0	0	0	0
0.25 - 0.50	6.6	2.5	1.7	0.7	0.4	0.2	0.1	0.1
0.50 - 0.75	20.4	7.9	5.3	1.8	1.3	1.0	0.9	0.9
0.75 - 1.00	27.0	16.0	10.7	3.9	2.5	2.0	1.7	1.6
1.00 - 1.25	23.1	21.1	17.1	7.6	5.1	3.4	2.9	2.5
1.25 - 1.50	12.7	18.9	18.3	11.0	7.5	5.4	3.9	3.4
1.50 - 1.75	5.5	12.4	14.5	13.5	10.9	7.1	4.9	4.2
1.75 - 2.00	2.0	8.1	11.6	14.1	11.8	9.2	6.2	5.1
2.00 - 2.25	1.0	5.4	7.4	11.3	12.1	10.7	7.7	6.6
2.25 - 2.50	0.5	3.2	4.7	9.6	11.2	10.6	8.4	6.9
2.50 - 2.75	0.2	1.7	3.2	7.7	8.7	10.3	8.7	7.0
2.75 - 3.00	0	0.9	2.0	5.9	6.9	8.4	9.4	8.2
3.00 - 3.25	0	0.6	1.3	4.2	5.9	7.2	9.0	9.5
3.25 - 3.50	0	0.4	0.7	2.6	5.0	6.2	8.3	8.8
3.50 - 3.75	0	0.2	0.4	1.7	3.2	4.7	6.7	7.3
3.75 - 4.00	0	0.2	0.4	1.3	2.1	3.8	4.9	6.7
4.00 - 4.25	0	0	0.2	1.0	1.4	2.9	4.1	5.2
4.25 - 4.50	0	0	0.2	0.8	1.2	1.9	3.4	4.4
4.50 - 4.75	0	0	0	0.4	0.9	1.4	2.4	3.3
4.75 - 5.00	0	0	0	0.4	0.7	1.0	1.7	2.0
5.00 - 5.25	0	0	0	0.2	0.4	0.8	1.3	1.6
5.25 - 5.50	0	0	0	0.2	0.3	0.6	1.0	1.3
5.50 - 5.75	0	0	0	0	0.2	0.5	0.7	0.9
5.75 - 6.00	0	0	0	0	0.2	0.3	0.5	0.7
6.00 - 6.25	0	0	0	0	0.1	0.2	0.5	0.5
6.25 - 6.50	0	0	0	0	0	0.2	0.5	0.5
6.50 - 6.75	0	0	0	0	0	0	0.2	0.5
6.75 - 7.00	0	0	0	0	0	0	0	0.3

Note: The tabular values for rainfall-rates of 0.01, 4.0, and 6.0 inches/hour, and for raindrops smaller than 0.5 mm were derived by extrapolation.

curves having been plotted for all the samples as explained above, the cumulative volumes were read from these curves at 0.25-mm intervals from 0.5 to 6.5 mm. These values and the rainfall-rates were then averaged for each group of ten. The per cent of the total volume within each 0.25-mm interval was then computed from the averages of each group.

Since considerable variation remained, the average percentage for each 0.25-mm interval for each group was tabulated on a diagram of size versus rainfall-rate. Free-hand curves of equal volume-percentage were then drawn to fit the tabulated data in a manner similar to that employed in making a topographic map.

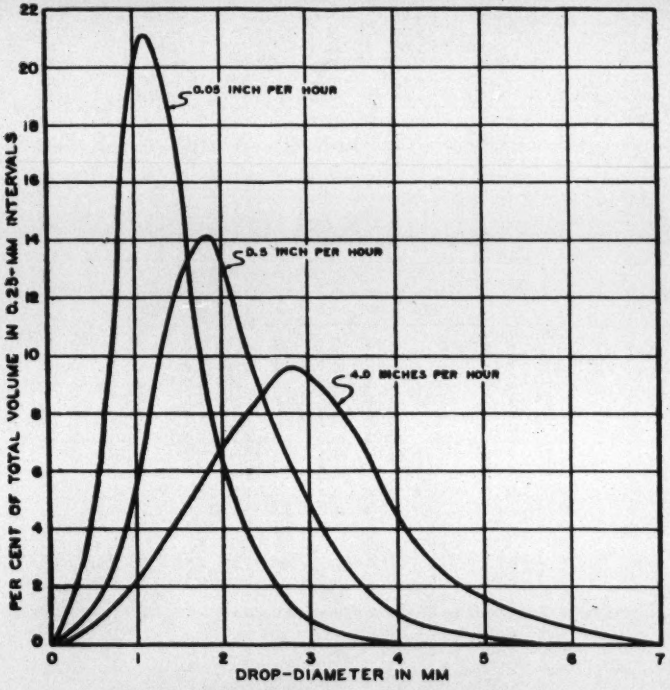

Fig. 3--Per cent of total volume contributed by drops of various sizes for three rainfall-rates, as computed for 0.25-mm intervals of diameter

To provide a means of determining the size-distributions at any rainfall-rate, cumulative-volume curves were drawn for each rainfall-rate represented in Table 3, and the drop-sizes at the 15 values for cumulative-volume percentage appearing on Figure 1 were plotted on this diagram, and smooth curves drawn through the points. To obtain a cumulative-volume diagram from these curves, plot the indicated cumulative volume against the corresponding drop-size at the intensity desired. If a tabulation of percentage of total volume within different size-limits is wanted, read values off the cumulative-volume curve at regular size-intervals and tabulate the difference between successive readings. Table 3 was prepared in this manner. When the volume-percentages are plotted against drop-size a typical bell-shaped frequency-curve is obtained. This is illustrated in Figure 3, which was prepared from the data of Table 3.

Determination of intensity--While concurrent measurements of intensity were made with a Fergusson-type weighing rain-gage, the correlation presented in Figure 1 has been based upon the mass of all the drops in the sample in almost all instances. Since the area of the pans was known and the duration of exposure was measured, the intensity could be found from the pellet-data, and the intensities computed in this manner gave a better correlation with drop-size. In a few instances, the duration of exposure was not measured; in a few others, it was too brief to be reliable. The poor correlation obtained with the recorded intensity is partly due to the failure of the instrument to record short-period fluctuations and partly to errors in determining the exact time at which the sample was taken. During periods of high rainfall-rate, the recording of this time was slighted in the rush to get as many samples as possible.

Discussion of results--The relation of median drop-size to rainfall-rate may be examined in Figure 1. Since the plotted data were taken from pans of 10-inch diameter, exposed for extremely brief intervals of time, a large part of the dispersion must be attributed to momentary and localized variations in the composition of the rain. It appears likely that if the drop-size were averaged over larger areas and for longer periods of time, the median drop-size would be a fairly strict function of rain-intensity. At the borders of storms, exceptions to this rule unquestionably exist. The occurrence of large-drop rains of low intensity at the beginning of thunder-storms is familiar to us all, but conditions such as this do not ordinarily persist and they probably represent an insignificant portion of the total rain.

The change in median drop-size over the range of intensities covered is quite small, increasing by only three diameters, while the intensity increases 400-fold. While a quantitative measure of the erosive power of rainfall, in terms of drop-size and velocity, is not yet available, it can be said that the erosive power of intense rainfalls per unit-volume will be significantly greater, because of their larger drop-size, than the erosive power of low-intensity rains.

A factor of the greatest importance to the erosion-producing potentialities of rain is the wind-velocity. A study of the relation of wind-velocity to intensity would be of considerable value

The close agreement of the measurements of LENARD and DEFANT with our own observations indicates that the relation found is not peculiar to the District of Columbia. It is possible that the same relation holds everywhere.

The upper limit of drop-size for intense rains is evidently about seven-mm diameter. This is considerably larger than supposed by Lenard and others.

The precision of the size-distribution determinations is much less than the values of Table 3 imply. The fractional percentages were carried because they give a better delineation of the largest and smallest sizes and because the sum of each such tabulation adds up to exactly 100 per cent, which affords an easy method of checking the accuracy of computations. As may be surmised from the scatter of data on Figure 1, the size-distribution at any rainfall-rate is only approximately known. Furthermore, considerable doubt exists as to the variability of size-distribution from time to time.

It was thought that some relation might be found between the drop-size and the cumulative rainfall, or perhaps the time elapsed since the beginning of the rain. While this phase of the question was studied, no correlations were discovered.

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DISCUSSION

G. W. MUSGRAVE (Soil Conservation Service, Washington, D. C.)--The earlier paper on the "Measurement of the fall-velocities of waterdrops and raindrops" [6] gave the velocities of falling waterdrops of different sizes and also the height of fall required to reach terminal velocity. The laboratory study indicated the need of determining drop-sizes in natural rainfall. The present study provides this information and the paper bears the marks of excellence in technique throughout. The authors themselves are perhaps their most severe critics, pointing out that "The precision of the size-distribution determinations is much less than the values of Table 3 imply." Nevertheless, the conclusion that "it appears likely that if the drop-size were averaged over larger areas and for longer periods of time, the median drop-size would be a fairly strict function of rain-intensity" is a reasonable one.

The data which are reported undoubtedly provide new information on a subject that quite inadequately has been touched upon in prior experimentation. The review of other work (especially that in Europe) is of itself particularly interesting and helpful.

The effects of energy of impact of falling drops upon soil-disintegration and upon infiltration of water into soil, have been previously noted. The paper "Analysis of runoff resulting from simulated rainfall on a paved plot" by C. F. IZZARD [pp. 500-509], indicates very clearly that the energy of falling raindrops imparts certain modifications to the flow-characteristics of surface-water not previously suspected. The vertical energy of the falling drop must be translated to horizontal energy in surface-flow with the result that flow-characteristics themselves are modified. As greater attention is directed to this problem, it seems probable that more attention will be given to the determination of energy-components in rainfall and surface-runoff, and for this purpose the present paper and the antecedent one will be found most useful.

Other workers (JOHN LAMB, JR., G. R. FREE, O. E. HAYS) in studies not yet complete and at present unpublished, are finding definite relations between rain-intensities and the rate of erosion. The explanation, in part at least, undoubtedly is found in the greater energy of impact of the larger drops naturally occurring in rains of higher intensity.

Meteorologists will be interested in these data and it is to be anticipated that they can provide hydrologists with information showing regional differences in storm-intensities (and consequently raindrop-size). Thus the relative amount of energy imparted by storms of different frequencies in various climatic regions may become known. Presumably this will lead to conclusions as to the relative need for protection of the land-surface in areas where there are distinct differences in storm-characteristics.

SOME RECHARGE-PHENOMENA OF A WASATCH PLATEAU WATERSHED

A. R. Croft and Richard B. Marston

Introduction--One of the biggest gaps in our knowledge of the hydrology of high watersheds of the Intermountain Region is the lack of understanding of the phenomena which occur from the time a deposit of snow begins to melt and the time that part of the melted snow-water appears as stream-flow. The part played by snow in watershed-recharge, snow-melting rates and the factors that influence them, movement of melted-snow water through the snow, overland flow beneath snow and on bare soil-surfaces, infiltration-capacities of snow-covered surface and subsurface-soils,

and duration and movement of gravitational water in the watershed-mantle, are some of the processes about which we have only meager knowledge, or none at all.

The purpose of this paper is to report results of measurements and observations of some of these phenomena on a 99-acre watershed, inside the Manti Forest, on the west face of the Wasatch Plateau in central Utah. This watershed is known as "A-B Drainage" and is one of the ten watersheds, which range from 9 to 1,645 acres in area, that are tributary to Ephraim Creek. The Intermountain Forest and Range Experiment Station is making comprehensive studies on the watersheds to determine the effect on stream-flow characteristics of mechanical water-flow-control structures located in the recharge-zone. The watersheds are now being calibrated for stream-flow. The data presented in this report are representative of those which are being secured during the calibration-period.

Description--A-B Drainage has its upper boundary on top of the Wasatch Plateau at 10,200-foot elevation and it slopes 17 per cent westward to a confluence with Ephraim Creek at 9,815-foot elevation. An automatic stream-gaging station is located just above the place where the stream joins Ephraim Creek. Soil-water observations were made in the upper center of the drainage at 10,100-foot elevation where the watershed-mantle is 6-1/2 feet deep. Figure 1 shows the character of this mantle and the upper two feet of bed-rock. The mantle is thinner near the crest of the plateau, and it is deeper and made up of coarser material near the main channel. The profile shown is a medium between these two conditions.

Vegetation is principally herbs, wheat and brome-grasses, and small scattered patches of Ribes inebrians, Ribes montigenum, and Abies lasiocarpa.

Method--Soil-water sampling was made possible by using two concrete-lined pits, seven feet deep, from which pipes project horizontally 32 inches into the soil. There are two sets of pipes in each pit located opposite each other and at distances of 3, 6, 9, 12, 18, 24, 36, 48, 60, and 72 inches below the ground-surface. They were placed in position without disturbing the soil by inserting them into holes of their exact size bored into the mantle. Pipes are staggered so that no pipe is closer than one foot in horizontal distance from any other pipe. The pits are provided with manways that reach above the deepest snow so that they may be entered at any time of year. The 40 pipes in the two pits were examined daily from the time snow-melting began until gravitational water disappeared below the pit-bottoms. Gravitational water was assumed to be level with or above each pipe-depth as long as free water dripped from the pipe. After free water disappeared soil-samples for moisture-determinations were taken by inserting a special auger into each pipe and withdrawing a sample of soil from beyond the end of the pipe.

The melting-rate of snow was determined by making daily measurements on a snow-measuring course 600 feet down-slope from the pits and also on two ten-acre areas located near the side boundaries and in the upper half of the drainage. Snow-cover was mapped daily on the ten-acre units and weekly on A-B Drainage.

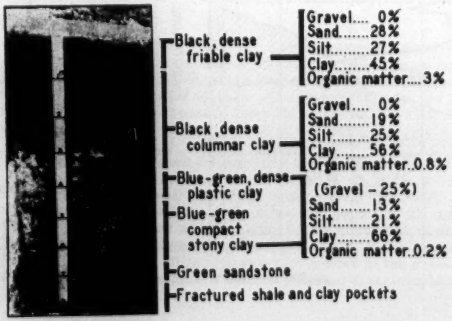

Fig. 1--Watershed-mantle profile at soil-water sampling pits

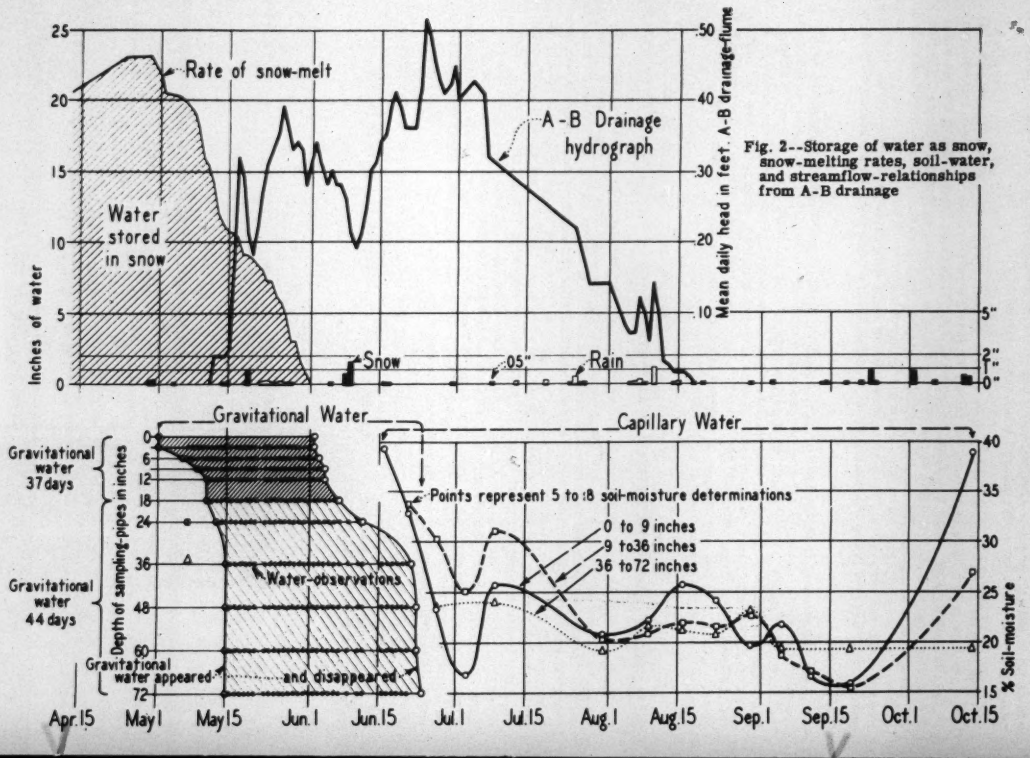

Fig. 2--Storage of water as snow, snow-melting rates, soil-water, and streamflow-relationships from A-B drainage

Stream-flow from the watershed was measured with a masonry V-bottom control-section that was equipped with a water-stage recorder. Stream-flow is shown in Figure 2 as depth-measurements because the control-sections on this and the other experimental watersheds are still in the process of being rated.

Results and discussion--Water stored in snow, rate of snow-melting, precipitation, gravitational soil-water, capillary soil-water, and stream-flow are shown graphically in Figure 2.

Snow-melting--Snow began to release water to the soil on April 29, when it contained 23 inches of stored water and when it had a density of 39 per cent. During the melting-period the density varied between 36 and 44 per cent and averaged 41 per cent. The lowest densities occurred immediately following snow-storms. The melting-rate varied from 0 inch to 1.97 inches of water daily and averaged 0.695 inch.

The daily melting-period was from about two hours after sunrise ($06^h\ 35^m$ Mountain Standard Time on May 20) to about one-half hour before sunset ($18^h\ 20^m$ Mountain Standard Time on May 20). No melting was ever detected between sunset and sunrise. A detectable crust began to form about one-half hour before sunset and the crust-temperature would sometimes drop as low as 8° below freezing even though the air-temperature remained several degrees above freezing throughout the night. The crust froze deepest on the coldest nights and exhibited a temperature-gradient which was lowest near the surface and increased gradually to 32° F at the point where it made contact with the soft snow. Because of this it was necessary that the temperature-deficit in the snow-crust be overcome each morning before melting began. This usually required from one to two hours after sunrise, depending on the coldness of the previous night, the thickness of the snow-crust, and intensity of insolation in the morning and no doubt upon other factors unknown.

All snow disappeared from the immediate vicinity of the water-sampling pits by June 1--33 days after release of water from snow began. The 99-acre watershed as a whole was, however, then only 50 per cent bare of snow, although, as shown by daily measurements made on the two 10-acre sampling units, 78 per cent of the water stored in snow on April 29 had been released.

As near as could be detected by numerous inspections, practically all melted-snow water entered the watershed-mantle. No overland flow was detected during the spring of 1941 other than from water returning to the surface through shallow aquifers.

Gravitational water--Gravitational water was noted in the pipe at three inches below the ground-surface on May 1--two days after the snow began to release water to the soil. The release of water amounted to 1.5 inches in the two days. Water was observed in the zone tapped by this pipe for 32 days, but it remained above this depth for only one day after the snow was gone from the immediate vicinity of the pits.

Water appeared at 18 inches below the surface on May 11, which was 12 days after release from snow began. The release during the 12 days amounted to 7.7 inches of water. Water was observed above the 18-inch depth for a total of 37 days, and for six days after all snow had melted near the pits.

Gravitational water passed from 18 to 36 inches in four days and then dropped rapidly from 36 to 72 inches, as it was observed in all pipes in this lowest zone on the same day--May 15. At this time 12.3 inches of the stored water--slightly more than one-half--had entered the soil. Water was observed in the 18- to 72-inch zone for 44 days. The water-table did not fall below the 72-inch pipe until 23 days after all snow had disappeared from the ground in the vicinity of the pits. Plant-roots in this zone were in free water from one to 23 days depending on their depth.

Penetration of gravitational water seemed unusually slow in the surface-soil, since it was 12 days after infiltration began before it was found 18 inches below the surface. Summer tests show that this soil will absorb six inches of water per hour under a five-inch head. The slow rate of infiltration observed in connection with melting of the snow may be due to the difficulty of displacing soil-air when the soil-surface is covered with a closely fitting blanket of snow as much as five feet deep. Penetration of water through the lower depths of the mantle in one day seems rapid in view of the slow movement near the surface. It is probable that breaks in the snow-cover and the lateral movement of water to small channels near the surface hastened air-displacement and permitted rapid penetration.

Gravitational water in the watershed-mantle on A-B Drainage moves laterally into gullies, channels, depressions, and rodent tunnels which are lower than the water-table, or it moves down-

ward through the mantle into shattered bed-rock beneath it. Lateral movement of water, especially in the most friable soil near the surface, is the course through which large quantities of gravitational water pass rapidly to the surface and to stream-channels. In the spring every gully or channel that lies below the water-table develops a small stream of water. As the water-table rises or falls, according to the rate of snow-melting, the shallowest channels exhibit intermittent flow, but the deepest channels usually flow continuously during and immediately following the period the snow is melting. The presence or absence of water in the channels is considered a rough gage of the height of the water-table. Only relatively small quantities of water appear to get through the mantle to aquifers in the bed-rock.

Gravitational water fills the mantle to the surface only when the most favorable snow-melting conditions exist for a week or more, and then water may flow directly over the surface to channels without first entering the soil. Flow of this character is not frequent and it was not observed on A-B Drainage in 1941.

Capillary water--The smoothed curves in Figure 2 show the trend of capillary water for the following depths: Surface to 9 inches; 9 to 36 inches; and 36 to 72 inches. Each plotted point represents five to 18 soil-moisture determinations. Moisture in the two upper zones declined sharply from the beginning of sampling (following the disappearance of gravitational water) until July 3, when an upward trend began. After July 9 the trend was gradually downward until about September 24, when snowfall and intermittent melting began to recharge the soil-capillary water. In the 36- to 72-inch zone the trend of the capillary water was gradually downward from July 9 to September 5, with only slight fluctuations during July and August. No change was noted in this zone after September 5, thus indicating that 3.23 inches of precipitation which occurred between September 13 and October 14 did not penetrate lower than 36 inches.

Rainfall that occurred between June 15 and September 15 added to the mantle no water that influenced stream-flow. Slight increases in stream-flow occurred on August 7 and 10, but this water either fell into flowing streams or ran over the surface to streams. Runoff from summer rainstorms is known to be as high as 83 per cent, depending on duration and intensity of rainfall, on the amount of vegetation and litter, and on the extent of soil-trampling by livestock. Overland flow from summer rainstorms is a common occurrence.

Moisture in the upper 36 inches of mantle reached a seasonal low of 16 per cent on September 15, which is two per cent below the calculated wilting-coefficient. This is probably about as low as transpiration and evaporation can reduce the moisture-content of this soil during an average season.

Recharge of the mantle began September 24 as a result of snow which melted slowly enough to permit complete infiltration of water into the mantle. Owing to almost complete stoppage of transpiration, and reduction in evaporation during the cool and often stormy days in fall, it is probable that rain or melted-snow water that penetrates the mantle after the middle of September are about as effective in watershed-recharge as equal amounts of water released from melting snow the following spring.

Stream-flow--Water appeared at the stream-gaging station on May 12, after nine inches of water had been released from the snow. This was one day after gravitational water had penetrated to a depth of 18 inches and three days before it was found at a depth of 72 inches. Peak-flow occurred on June 24--23 days after all snow near the sampling pits had melted. At this time the 99-acre watershed was only eight per cent covered with snow and about 98 per cent of the total water stored in snow on the entire watershed had been released.

The period from May 12 to June 24, which included the peak-flow and more than half the total annual discharge of the stream, corresponded very closely with the presence of gravitational water in the mantle. This close relationship, together with the fact that peak-flow occurred when only eight per cent of the drainage was covered with snow and after 98 per cent of the water stored in snow had melted, indicates that the principal source of high spring runoff from A-B Drainage is the yield of water from the saturated mantle--not overland flow of melted-snow water.

Studies of all the phenomena reported in this paper except stream-flow and precipitation have been discontinued for the duration of the war. It is hoped that the complete study may be revived and continued soon after victory is won.

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DISCUSSION

W. G. HOYT (U. S. Geological Survey, Washington, D. C.)--The reported absence of overland runoff and the rapid passage of water through interstices of soil-mantle and into snow-rivulets and gullies are phenomena that are believed to be quite common, not only during periods of snow-melt but also during periods of rain. When the gage-heights at the wier on the experimental area have been translated into discharge it will be possible to determine rates and amount of soil-retention and total abstraction from the snow-melt. Such information should be of immediate and special interest in all problems concerning the runoff from snow-covered mountain-areas, including its probable magnitude and distribution with respect to time.

In land-use problems the observational data no doubt have definite value in the determination of ways and means to provide for the maximum rate of entry into and the maximum capacity of the soil-column.

Through the thousands of infiltration-observations which have been made, a fund of information is being made available concerning rates of entry of water into the soil-mantle and rates of overland runoff. The hydraulic laws governing the movement of water after it has reached definite channels are also fairly well known. As the authors state, the biggest gap in our knowledge of runoff-phenomena is our lack of understanding as to what takes place between the entrance of water into the soil-column and its appearance as stream-flow. Observations such as described by the authors aid materially to bridge this gap.

COMPARISON OF f-CURVES DERIVED BY THE METHODS OF SHARP AND HOLTAN AND OF SHERMAN AND MAYER

L. K. Sherman

The derivation of f-curves of infiltration-capacity from natural rainfall has been undertaken by only a few hydrologists. The use of the infiltrometer does not supplant the necessary for f-curves on large or small areas based on natural rainfall. Infiltrometer f-curves, excepting f_c-values, do not agree with natural rainfall f-curves.

Each of the accompanying Figures 1, 2, and 3 shows a comparison of natural rain f-curve derived by two entirely independent procedures from the same data. The solid lines show the f-curve derived by the SHERMAN and MAYER [see 1 of "References" at end of paper] method and the dotted lines show the same f-curve derived by SHARP and HOLTAN method [2].

The close agreement between the two is an evidence of the correctness of both methods.

Figures 1, 2, and 3 correspond with Figures 1, 6, and 9 of Sharp and Holtan. They used clock-time regardless of time-intervals when rain fell at rates less than the existing infiltration-capacity. When time-condensation is properly applied to such intervals, it furnishes the true f-curve given by the dotted lines.

The Sherman and Mayer f-curves were copied from their curve-type or C_b-diagram. Selection of the curves was made through Sharp and Holtan's rainfall-runoff data utilizing the formula: Type-curve, or C_b-number = $[(f_a - f_c)/f_a]$.

Time-condensation in deriving infiltration-capacity curves--Sharp and Holtan derived mass-curves of infiltration and f-curves platted to observed clock-time. In Figures 1, 2, and 3, we have applied the final essential step--that is, time-condensation. What is time-condensation? Time-condensation is a procedure called for in the derivation of an f-curve whenever the observed rain-intensity is less than the infiltration-capacity.

By definition, the infiltration-capacity curve must show, at any period, the duration of time required for a given volume of infiltration to take place at capacity-rate.

Figure 4 shows a pattern or sequence of hourly downpours and intensities. The rain lasted for nine hours. Excess rain prevailed throughout except during the fourth hour. The f-curve for the first three hours can be platted as shown by one of several methods in current practice. During the fourth hour, the rain-intensity dropped to 0.19 inch in one hour. Capacity-rate during hour 4, on Figure 4, is obviously about twice the rate of 0.19 inch for the hour. By the dotted line.

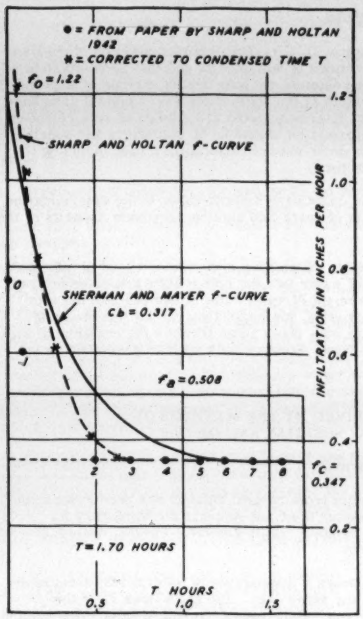
●= FROM PAPER BY SHARP AND HOLTAN 1942
*= CORRECTED TO CONDENSED TIME T
f_0 = 1.22
SHARP AND HOLTAN f-CURVE
SHERMAN AND MAYER f-CURVE
Cb = 0.317
f_8 = 0.508
f_c = 0.347
T = 1.70 HOURS
T HOURS
INFILTRATION IN INCHES PER HOUR

Fig. 1--Curve of infiltration-capacity, SCS plot 6, La Crosse, Wisconsin, corn in rotation, storm of September 7, 1941 (Rain = 1.55 inches, runoff = 0.64 inch, volume-infiltration = 0.86 inch)

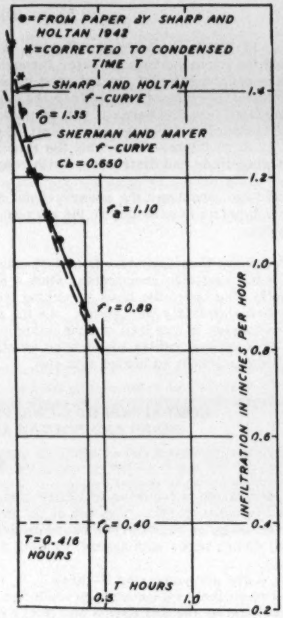
●= FROM PAPER BY SHARP AND HOLTAN 1942
*= CORRECTED TO CONDENSED TIME T
SHARP AND HOLTAN f-CURVE
f_0 = 1.35
SHERMAN AND MAYER f-CURVE
Cb = 0.650
f_8 = 1.10
f_1 = 0.89
f_c = 0.40
T = 0.416 HOURS
T HOURS
INFILTRATION IN INCHES PER HOUR

Fig. 2--Curve of infiltration-capacity, SCS plot 4, La Crosse, Wisconsin, barley and meadow in rotation, storm of June 7, 1940 (Rain = 1.25 inches, runoff = 0.720 inch, volume-infiltration = 0.465 inch)

a projection of the f-curve beyond hour 3, we note that infiltration-capacity for the first half of hour 4 is 0.38 inch per hour. That is to say, the duration of infiltration-capacity rate would require only one-half hour to permit infiltration of all of this 0.19 inch of rainfall. The condensed time T in this case is 0.5 hour.

Let us check the foregoing in another way. The volume under an f-curve, or any section thereof, equals the observed volume of infiltration. If the hour 4, of no excess rain, is omitted, as is often done, then the volume of infiltration under the full f-curve will be 0.19 inch too small. If the whole of hour 4 is included, then the volume under the f-curve will exceed the measured volume of infiltration by something slightly under 0.19 inch. With time-condensation applied, the total volume by the f-curve is identical with the total observed volume of infiltration, and both the f-curve and the mass-curve are smooth curves through all points.

In a case like Figure 1 of Sharp and Holtan, excess rain fell at only every other hour. Time-condensation may make large differences in the f-curve. Time-condensation is essential in dealing with natural rainfall-patterns.

In general terms, the following equations hold true for mass-curves:

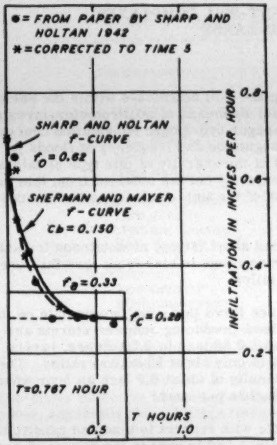

Fig. 3--Curve of infiltration-capacity, SCS plot 3, La Crosse, Wisconsin, continuous corn, storm of July 8, 1938 (Rain = 0.74 inch, runoff = 0.46 inch, volume-infiltration = 0.26 inch)

$$(T/1) = (1/f) \quad (1)$$

$$\text{Total volume of infiltration} = f_a \times \text{total } T \quad (2)$$

$$\text{Total volume of infiltration} = \Sigma(f \times \Delta T) \quad (3)$$

where T is condensed time, t = duration of non-effective rain (one hour), i is intensity of non-effective rain, f is infiltration-capacity, and f_a is average infiltration-capacity for the storm-duration T.

Mr. Holtan calls attention to the fact that surface-detention supplements non-effective rainfall; thus, for example, in hour 4 of the foregoing, if surface-detention was 0.10 inch, it would increase the volume of infiltration to 0.29 inch and increase the duration of condensed time to (0.29/0.37) or 0.77 hour instead of 0.5 hour.

References

[1] A. L. SHARP and H. N. HOLTAN, Trans. Amer. Geophys. Union, pp. 578-593, 1942.

[2] L. K. SHERMAN and L. C. MAYER, Trans. Amer. Geophys. Union, pp. 666-677, 1941.

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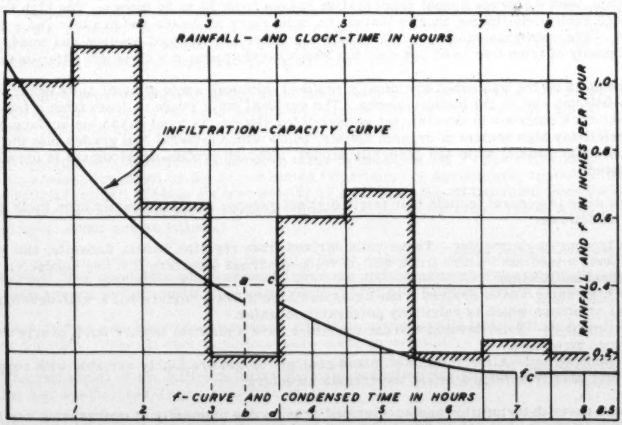

Fig. 4--Time-condensation (when line c-d is moved one-half hour on to line a-b, then f-curve conforms with scale of condensed time "T")

INFILTRATION-CAPACITIES OF SOME PLANT-SOIL COMPLEXES ON UTAH RANGE WATERSHED-LANDS

Lowell Woodward

Introduction--The infiltration-capacity of a number of plant-soil complexes within the Sevier Lake Watershed of south-central Utah was determined in 1941 by means of infiltrometer-investigations. These data were obtained primarily to supplement meager hydrologic information concerning the effect of watershed-improvement measures on the magnitude and frequency of floods in connection with a flood-control survey of that area. In view of the scarcity of this type of data and its possible usefulness elsewhere, the average infiltration-capacity curves obtained from this investigation are herein presented together with an explanation of the field-techniques and statistical methods used in their derivation.

The area of study--Floods occur in many of the numerous short, steep, mountainous tributaries within the Sevier Lake Watershed. The flooding tributaries range in size from less than one to 290 square miles, the average size being about four square miles.

The most destructive floods are heavily debris-laden flash flows that usually originate on portions of the headwater-areas during summer storms. The flood-producing summer storms are of the cloud-burst type. They range in magnitude from only about 0.50 inch to 2.50 inches, rarely last longer than 90 minutes, and commonly occur over areas of only about 20 square miles. The 0.5-inch storm generally attains a maximum five-minute intensity of about 0.9 inch an hour whereas the 2.50-inch storms attain maximum intensities of 4.80 inches per hour.

The plant-cover on the tributary-slopes is highly variable with respect to kind and condition of the vegetation due in part to local climatic and edaphic factors and in part to the degree of past grazing-use. In general, there are three major zones or classes of vegetation as follows:

(1) Sagebrush-pinyon pine-juniper-desert shrub--These relatively low-density stands occur on the foothill-areas where precipitation averages about ten inches annually. Grasses and weeds are usually intermixed with the shrubs, but litter is generally lacking.
(2) Mountain brush-woodland--These relatively dense stands occupy the slopes at intermediate elevations, where average annual precipitation is about 20 inches. Grasses and weeds usually occur as an understory and the surface-soil normally includes a fairly complete mantle of litter.
(3) Aspen-conifer-open grasslands--These plant-cover types occur in the headwaters at high elevations, where average annual precipitation ranges from 25 to 35 inches. The high forests of aspen and coniferous timber usually include an understory of shrubs and grasses and a dense mat of litter. The open grasslands usually include a mixture of perennial grasses and weeds which attain a density of from five to 50 per cent but which rarely produce a complete litter-mantle.

The soils on the watershed are mostly residual, although some alluvial soils occur in the canyon-bottoms and on the foothill-slopes. The residual soils range in depth from a few inches or less near rock outcrops to several feet on stabilized slopes. In most cases the surface-horizon has a relatively high content of organic matter, below which mineral soil grades into the parent material. The alluvial soils are generally deeper, although profile-development is usually less pronounced.

The soils in general include four fairly distinct groups, based primarily upon their geologic origin, as follows:

(1) Igneous-metamorphic--These soils derived from rhyolite, basalt, andesite, and quartzite, usually have a medium texture and a well-developed porous structure that are conducive to relatively rapid infiltration.
(2) Limestone--Soils derived from limestone have a heavy texture but a well-developed porous, colloidal structure which is relatively permeable to water.
(3) Sandstone--Soils developed from sandstone have a medium texture but a poorly developed, impervious structure.
(4) Redeposited--Alluvial soils of mixed geologic origin are highly variable with respect to texture but usually develop a fairly impervious structure.

Plant-cover deterioration and accelerated erosion due primarily to overgrazing are common on the slopes of the watershed. The usual manifestations of deterioration include a marked decrease in the total density of the plant-cover, the replacement of palatable grasses and shrubs by less palatable species, a decrease in the amount of surface-litter, and sheet- and gully-erosion.

Table 1--Number and distribution of infiltrometer sample-plots

Plant-cover	Soils			
	Igneous-metamorphic	Sandstone	Limestone	Redeposited
Browse-shrub				
Low density	4	4	3	a
Medium density	4	4	2	a
High density	4	4	2	a
Sage-pinyon-juniper				
Low density	4	5	b	4
Medium density	4	5	b	5
High density	5	7	b	4
Herbaceous				
Low density	3	4	4	a
Medium density	3	4	4	a
High density	4	4	4	a

[a]Not found on the watershed. [b]Omitted from schedule because of inconsequential occurrence.

The major objective of watershed-improvement measures is to increase the density of the plant-cover, especially the palatable forage species, and to prevent erosion.

Plant-soil complexes studied--Infiltration-investigations were restricted to nine of the most extensive and important complexes or combinations of plant-cover types and soils, as follows: (1) Browse-shrub on igneous-metamorphic soils; (2) sage-pinyon-juniper on igneous-metamorphic soils; (3) herbaceous cover on igneous-metamorphic soils; (4) browse-shrub on sandstone soil; (5) sage-pinyon-juniper on sandstone soil; (6) herbaceous cover on sandstone soil; (7) browse-shrub on limestone soil; (8) herbaceous cover on limestone soil; and (9) sage-pinyon-juniper on redeposited soil.

Detailed surveys of the plant-and-soil mantle on the watershed as a whole showed that total plant-cover density was the most reliable single factor-index of the relative condition of each plant-soil complex. The factor of plant-cover density therefore was adopted as a quantitative index of the extent to which the complexes would be changed by watershed-improvement measures. Accordingly, the infiltrometer-studies were so designed as to include measurements of a wide range of plant-cover densities in each of the complexes sampled.

The sampling scheme adopted for the infiltration-study included 108 plots. These were selected so as to obtain from seven to 17 samples on each of the nine complexes (Table 1). The plant-cover density on the plots ranged from one to 75 per cent.

Field-procedures--Infiltration-tests were made by means of the F-type infiltrometer. This portable apparatus, developed by the United States Department of Agriculture, applies water in the form of artificial rainfall to plots six feet wide by 12 feet long. Runoff collected from the plot is used as a basis for calculating the infiltration-capacity of the tested area. The detailed procedures in chronological order are as follows:

(1) The plot-boundaries were set in the soil without disturbing the vegetation, litter, or soil within the plot. The vegetation which extended over the plot-boundaries was clipped off even with the boundaries to prevent it from taking water on or off the plot by interception and stemflow.

(2) Each plot was sprinkled for two hours with lawn sprinklers 24 hours prior to each infiltration-determination. Thus all determinations were made on wet soil.

(3) The remainder of the infiltrometer-equipment, including the collecting trough, rainfall-applicator, and windbreaker-frame, was then set up.

(4) The density of the plant-cover on each plot was estimated by at least two experienced estimators using the square-foot density method [see 1 of "References" at end of paper]. The average of the estimates was recorded as the percentage-density.

(5) Artificial rainfall was applied at a constant rate. Low intensities, about two inches per hour, were used on all plots where the infiltration-capacity was less than one inch per hour after 30 minutes of application. High intensities of about 4.0 inches per hour were used on all other plots. In a few cases the infiltration-capacity of the soil was greater than the rate of rainfall which could be applied, in which cases the final capacity was recorded as the "rainfall-rate plus"

(6) Runoff was collected in three-gallon buckets and weighed at one- or two-minute intervals throughout the entire determination. Runoff was calculated in terms of surface-inches per hour and plotted as the runoff-curve. The data were calculated and plotted in the field as soon as each reading was obtained.

(7) Eroded material in the runoff-water was measured by means of soil-colloid hydrometers [2]. These hydrometers were calibrated to read grams of material per liter of water.

(8) Rainfall-application was continued until runoff became constant, or for a maximum period of 140 minutes. At the end of this period hoods were slid over the applicator-nozzles to stop rainfall from falling in the plot. After the rainfall was stopped, runoff was measured at intervals of one-half minute to obtain a record for the recession-hydrograph. While the applicator-nozzles were hooded, the trees, brush, and other tall vegetation were removed and a waterproof tarpaulin placed over the plot. The applicator-hoods were then removed so as to permit rainfall again to fall on the plot at the original rate. Runoff from the tarpaulin-covered plot was measured to determine the rate of application. This method of measuring the rate of rainfall has been found highly satisfactory [3].

(9) A test-pit was dug in each plot after the determination to ascertain the depth of water-penetration and the soil-profile characteristics.

Methods of analysis--Corrections: The runoff-curves were corrected for surface-storage and volume of eroded material. The surface-storage corrections were based on the recession-hydrograph. These corrections were essentially constant for all plots and were equivalent to moving the runoff-curves laterally about three minutes toward zero-time. The eroded-material corrections were based on the hydrometer-measurements and were applied over the entire curve. The corrections were relatively slight in most cases.

Rainfall and runoff were calculated for a slope-area of 72 square feet. Because some of the plots were on slopes ranging in steepness up to 65 per cent, rainfall minus runoff was corrected in all cases to the true horizontal area of each plot.

Actual infiltration-capacity curves: The corrected values of rainfall minus runoff were plotted as actual infiltration-capacity curves. Thus 108 curves were obtained from the nine complexes and from the widely varying plant-cover densities.

All of the curves were checked for conformance with HORTON'S infiltration-equation [4], which is of the form

$$f = [f_c + (f_o - f_c)e^{-K_f t}]$$

where f = infiltration-capacity in inches per hour, f_c = final or constant infiltration-capacity, f_o = infiltration-capacity at zero-time, e = 2.71828 or the base of the Naperian logarithms, K_f = a constant which expresses the shape of the infiltration-capacity curve and is equal to the negative slope of the straight line which best fits the points log $(f - f_c)$ against time, when time is the abscissa, and t = time in hours.

Curves derived from Horton's equation in all cases were found to be practically identical to the original curves, except for the values at zero-time and a few minutes thereafter. These discrepancies, however, were relatively insignificant.

Relationships of plant-density and infiltration: Further inspection of the infiltration-capacity curves strongly suggested a definite relationship between the plant-density and such important characteristics of the curves as Horton's f_c (the final infiltration-capacity), Horton's K_f (the shape of the curve), and V (the volume of infiltration per unit-area above the final capacity). Curves from plots having high plant-cover densities in general appeared to have higher final infiltration-capacities (f_c), lower values of K_f and higher values of V than similar plots with low densities.

The validity of the apparent relationships between plant-cover density and the factors f_c, K_f,

Table 2--Correlation-coefficients and regression-equations showing the relation between density and the constants f_c, V, and K_f

Complex	No.[m]	Density versus f_c			Density versus V			Log density versus log K_f		
		Correlation-coefficient	Regression-equation[n]		Correlation-coefficient	Regression-equation[o]		Correlation-coefficient	Regression-equation[p]	
			(a)	(b)		(a)	(b)		(a)	(b)
Browse-igneous	11	+.882	+.61	+.090	+.772	+.39	+.043	-.788	+1.120	+0.464
Sage-igneous	13	+.864	+.69	+.106	-.530	+.55	-.013	-.520	+1.520	-0.822
Herbaceous-igneous	9	+.728	+.38	+.021	+.377	+.22	+.004	-.467	+1.262	-0.223
Browse-sandstone	13	+.455	+.66	+.031	+.716	+.38	+.021	+.273	+0.578	+0.077
Sage-sandstone	17	+.236	+.44	+.014	+.500	+.63	+.030	-.640	+1.179	-0.418
Herbaceous-sandstone	10	+.361	+.15	+.005	+.604	+.09	+.005	-.337	+1.400	-0.250
Browse-limestone	7[q]	+.636	+1.68	+.039	+.996	+.03	+.035	-.995	+2.887	-2.040
Herbaceous-limestone	12	+.546	+.18	+.025	+.784	-.45	+.053	-.183	+1.118	-0.229
Sage-redeposited	14	+.361	+.59	+.014	+.674	+.04	+.061	-.095	+0.504	-0.042

[m]Numbers refer to actual number of reliable values; the total is less than 108 because on some plots it was impossible to apply enough water to obtain accurate values of f_c, V, and K_f.

[n]Regression-equation is $f_c = a + (b \times \text{density})$, where a and b are the constants shown.

[o]Regression-equation is $V = a + (b \times \text{density})$.

[p]Regression-equation is $\log K_f = a + (b \times \log \text{density})$.

[q]Only three reliable values were obtained for V and K_f because of exceptionally high infiltration-capacities on plots having high densities; however, reliable values were obtained for f_c on all seven plots.

and V were determined by means of correlation-coefficients after which specific relationships were developed from regression-equations (Table 2). In the first step of this analysis some of the correlation-coefficients were found to be highly significant, some significant, and others not significant. Lack of statistical significance in some of the cases, however, is believed to be due to the small number of samples.

As a further check on the validity of the general relationship between density and the various factors, correlation-coefficients of like variables were combined for all complexes by FISHER'S Z-transformation method [5]. The combined coefficients thus obtained for density against f_c, density against V, and log density against log K_f were found to be 0.56, 0.52, and -0.40, respectively. For the number of samples involved, +0.30 is highly significant, which clearly indicates that these relationships are valid. In view of the statistical validity of the relationships it was therefore assumed that regression-equations offer the best means for obtaining average values of f_c, V, and K_f under specific conditions of plant-cover density.

Derived infiltration-capacity curves for specific plant-cover densities--Average values of f_c, V, and K_f were calculated from the regression-equations for various plant-densities on each complex. Values were calculated for densities of 5, 15, and 25 per cent on all complexes and for densities of 35 and 45 per cent on some of the complexes. Curves that satisfied these values were then derived.

The derived average curves (Fig. 1) show that infiltration-capacities on the watershed-slopes range from values sufficiently high to preclude the possibility of runoff from some areas during all but the most intense storms expected, to values so low as to suggest the possibility of runoff from practically all storms on other areas. In general, infiltration-capacities were greatest in browse-shrub-cover types and on igneous-metamorphic and limestone soils. They were lowest in herbaceous-cover types and on sandstone and redeposited soils.

Infiltration-capacities increased directly with increases in plant-cover density although the

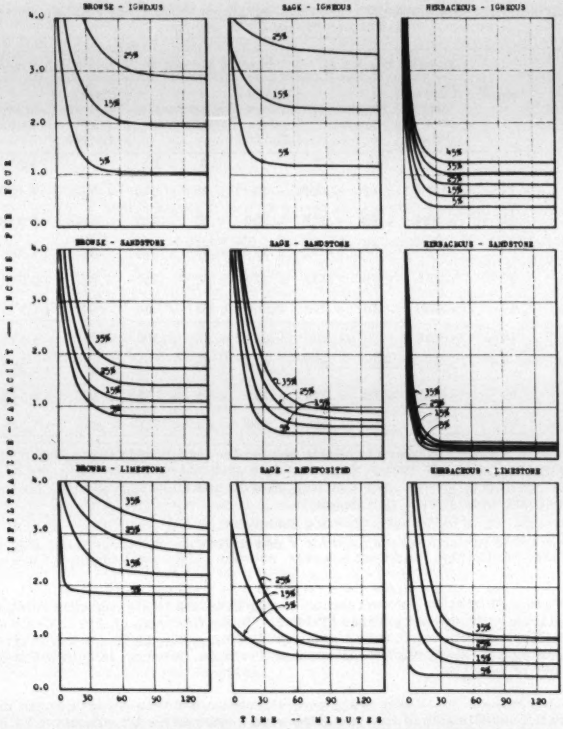

Fig. 1--Average infiltration-capacity curves for various plant-cover densities on selected plant-soil complexes, Sevier Lake Watershed, Utah

magnitude of the increases varied between cover-types and soils. Infiltration-capacity increases were greatest for a given increase in plant-cover density within the browse-shrub type and on igneous-metamorphic and limestone soils. They were least within the herbaceous plant-cover type and on the sandstone and redeposited soils. Since runoff is, roughly, inversely proportional to infiltration, the relationships noted in this study clearly indicate that measures aimed at increasing the plant-cover density will be relatively more effective in reducing peak-flow discharges when applied to the browse-shrub and sagebrush-pinyon-juniper types than to herbaceous areas.

Hydrographs of several of the tributaries within the Sevier Lake Watershed were synthesized by means of average rainfall-intensity patterns and the derived average infiltration-capacity curves of the various plant-soil complexes. The synthesized hydrographs closely approximated recorded flood-discharges. It is recognized that these checks are not conclusive but in view of the essential agreement with the discharge-records, it is believed that the infiltration-capacity curves are reasonably accurate.

References

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DISCUSSION

ROBERT E. HORTON (Voorheesville, New York)--There is much to commend in this paper. It should be read by everyone about to undertake similar investigations, and there are several points in the methodology, both of experiment and analysis, used by Woodward which should be generally adopted. Because of the importance of these matters they will be briefly summarized.

(1) Runoff should be expressed in terms of net water-runoff-not as the total runoff, including silt.

(2) The best basis for the comparison of infiltration-characteristics of different classes of terrain is through the use of the infiltration-constants f_0, k_f, and f_c.

(3) On steeper slopes, rainfall, runoff, and infiltration-capacity should be expressed as depth on the projected or horizontal area--not as that on the slope or plat-area. Rainfall and runoff on larger areas are always expressed in terms of depth on map or projected area and results of sprinkled-plat experiments are needed in that form for practical use. Slope may make little difference if less than ten per cent. If the length of the infiltrometer-plat is ℓ and the slope angle α, then the ratio of the projected to the total area is $\ell \cos \alpha$, and for a 30° slope the infiltration-capacity per unit of projected area is 15.5 per cent greater than that per unit of actual soil-surface area.

(4) Infiltration-capacity is not the difference between rainfall and runoff but, as pointed out by Woodward, per unit-time interval it is equal to the rainfall minus the sum of the runoff and the increment of the surface-detention.

(5) It is important to get complete and accurate data of residual runoff-graph, as Woodward did, for use in determining infiltration-capacity.

From an analysis of experiments by NEAL with bare, artificially packed soil, the writer [1] found that the time required to reduce infiltration-capacity from its initial value f_0 to its constant value f_c varied inversely as the rainfall--in other words, that for a given raindrop-size a constant or nearly constant amount of energy of impact from falling rain is required to bring about the transformation of the soil-surface which reduces the infiltration-capacity from f_0 to f_c. In case of Neal's experiments on bare soils this quantity of rain was three inches. This result was confirmed in an analysis of 192 experiments on natural soils in Mississippi by AREND and HORTON [2]. In the latter experiments it was found that on grass and wheat-stubble, doubling the rain-intensity reduced the time required to change from f_0 to f_c about one-half. On corn-stubble, on a soil which eroded heavily, this result did not hold true as surface-erosion maintained continually a new soil-surface exposed to impact of rain.

These studies led the writer to suspect that cover-density may have a pronounced effect on the time required to reduce infiltration-capacity to f_c for a given condition. Woodward's experiments confirm this suspicion. Referring to Figure 1, if the curves for a given complex are shifted horizontally so they coincide at a given point, then taking this as the value of f_0 and measuring time from this point, it will readily be seen that in most cases the time elapsed before the infiltration-capacity becomes sensibly constant increases nearly in proportion to the cover-density. The writer has used t_c to designate the time-interval required to reduce the infiltration-capacity from

a given initial value f_0 to within one per cent of its final constant value f_c and has designated this the critical time. The critical time is related to the parameter k_f through the equation

$$t_c = (1/k_f \ln_{100} [(f_0 - f_c)/f_c])$$

Woodward has given regression-equations for k_f in terms of cover-density and it is easily possible to extend his results to include regression-equations for t_c in terms of k_f. It appears that the increased cover-density breaks the force and reduces the energy of impact of the falling rain and so has much the same effect on k_f and t_c as a reduction of rain-intensity.

This raises the question whether the curves in Figure 1 are all really comparable or not with respect to k_f and t_c.

It is apparent that in the case of these experiments increased cover-density had a threefold effect on infiltration-capacity characteristics:

(1) Other things equal, the greater the cover-density the higher the initial infiltration-capacity. Woodward's experiments bring this out strikingly, as all of the plats were thoroughly wetted 24 hours previous to the experiments.

(2) Increased cover-density is accompanied by increase in the final or constant infiltration-capacity f_c. This increase of f_c is probably quite complex and due to different causes in different cases, the two major factors being the reduction in impact-effect and the tendency for a better soil-structure and a more open structure as a result of protection of biologic structures in the surface-layer of the soil by the cover and the humus it provides.

(3) other things equal, increased cover increases the value of t_c or the duration of rain during which the infiltration-capacity remains above its minimum value f_c. This is not important in case of floods produced by prolonged storms but it may be highly important in case of floods produced by short, intense rains.

Woodward's paper presents in practical working form quantitative data valuable not only for purposes for which they were obtained but for many other purposes as well. Recognition of the value of such data in other fields of hydrology than soil-conservation has not been as general as it should be. A single example will serve as an illustration. Two separate Federal agencies made estimates of the spillway-capacity required for a proposed reservoir. There were stream-flow records covering 40 years or more on the same stream at two locations. It was known that some change had taken place and that higher floods had occurred prior to the beginning of the records than during the period they covered. Making allowance for this but basing the estimates primarily on the recorded flood-flows, one agency arrived at a required spillway-capacity of 83 second-feet per square mile; the other, using a different method, arrived at a spillway-capacity of 158 second-feet per square mile, or nearly twice as much. The highest recorded flood-discharge on the stream was 55 second-feet per square mile. The higher estimate of spillway-capacity was obtained by plotting a scatter-diagram of maximum recorded flood-intensities for a large surrounding region in terms of drainage-area, drawing a line to envelop all but two or three of the highest points and using this as a relation line between flood-intensity and size of drainage-area, wholly disregarding the possible differences in flood-producing capabilities of the different drainage-basins. Such differences may be large even though the rainfall on the different basins is much the same.

Experiments such as those reported in Woodward's paper furnish a basis for a more scientific as well as much accurate approach to such a problem. Comparing, for example, two areas of equal size, one with 75 per cent igneous-herbaceous cover with 35 per cent density and 25 per cent lime-herbaceous cover with 15 per cent density, the other with 75 per cent lime-herbaceous cover and 25 per cent indigenous-herbaceous cover with 35 per cent density, in a storm of rainfall-intensity 1.5 inch/hour, lasting long enough to bring the surface-runoff up sensibly to equality with the difference between rain-intensity and f_c, the surface-runoff intensities from the two areas would be as shown in Table 1. Area "A" would yield a surface-runoff intensity of 448 second-feet per square mile as compared with 750 second-feet per square mile from area "B", or for drainage-areas of 100 square miles each, the direct surface-runoff from area "A" would be 44,800 cfs, that from area "B" 75,000 cfs, both with the same rainfall.

Differences in actual flood-intensities would of course be somewhat affected by channel-storage and, in spite of these differences in flood-intensity, the total or annual runoff from the two areas might be nearly the same. This would be true if most of the increased infiltration on the more permeable area ultimately reached the stream as ground-water flow. Differences in flood-

Table 1--Effect of cover-type and density on flood-producing capabilities of different areas, with rain-intensity 1.5 inch/hour

Cover-type (1)	Density (2)	f_c (3)	i (4)	$(i - f_c)$ (5)	Per cent area (6)	Weighted runoff (7)
	pct					in/hr
Area A						
Igneous-herbaceous	35	1.00	1.50	0.50	75	0.375
Lime-herbaceous	15	0.20	1.50	1.30	25	0.325
Total	...	.....	.....	.....	...	0.700
Area B						
Igneous-herbaceous	35	1.00	1.50	0.50	25	0.125
Lime-herbaceous	15	0.20	1.50	1.30	75	0.975
Total	...	.....	.....	.....	...	1.10

runoff intensity of the same order of magnitude as those given in this illustration were actually observed in connection with the Little Tallahatchie Drainage-Basin, where, owing to somewhat unusual conditions, surface-runoff rarely occurs from soil well protected by forest-cover. It was found that for different subdivisions of this drainage-basin the flood-intensities in the same storm could be quite accurately represented by multiplying the runoff-intensity for an area without forest-cover by the percentage of a given area without forest-cover.

Differences in soil-cover complexes and densities of cover are apparently far more important than some of the factors hitherto considered in estimating flood-discharges, under summer conditions. Under winter conditions, with frozen ground, these effects may largely disappear. In any event the examples given serve to show the fallacy of the assumption that underlies the use of the scatter-diagram of flood-intensities, namely, that any area in a given region will produce as great a flood-intensity as any other area in the same region.

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THE DETERMINATION OF INFILTRATION-RATES ON SMALL AGRICULTURAL WATERSHEDS

A. W. Zingg

The purpose of this paper is to illustrate the workability of applying the more recent techniques developed for determining, from precipitation and runoff data, the infiltration-rate during storm-runoff.

The specific illustration is a continuous precipitation-period of 31.5 hours, which occurred October 30, 31, and November 1, 1941. Total precipitation from the storm was 2.03 inches. Its average intensity was 0.06 inch per hour, and the maximum intensity was 0.33 inch per hour for one ten-minute period. Six and one-half inches of rainfall during the month of October preceded the storm. This storm was of wide scope and was characteristic of storms in the late fall months. A decrease in the infiltration-rate over large areas undoubtedly caused the flood-stages reached by many of the larger streams throughout the midwest following this prolonged storm of low intensity.

Data obtained from one of the small agricultural watersheds of the Research Division of the Soil Conservation Service is exemplary of runoff from the storm. This watershed is on the Shelby soil at Bethany, Missouri. It is 7.5 acres in area, has an average slope of 6.5 per cent, and was contour-drilled to corn in 1941. A detailed description of the watershed is contained in a previous publication [see 1 of "References" at end of paper].

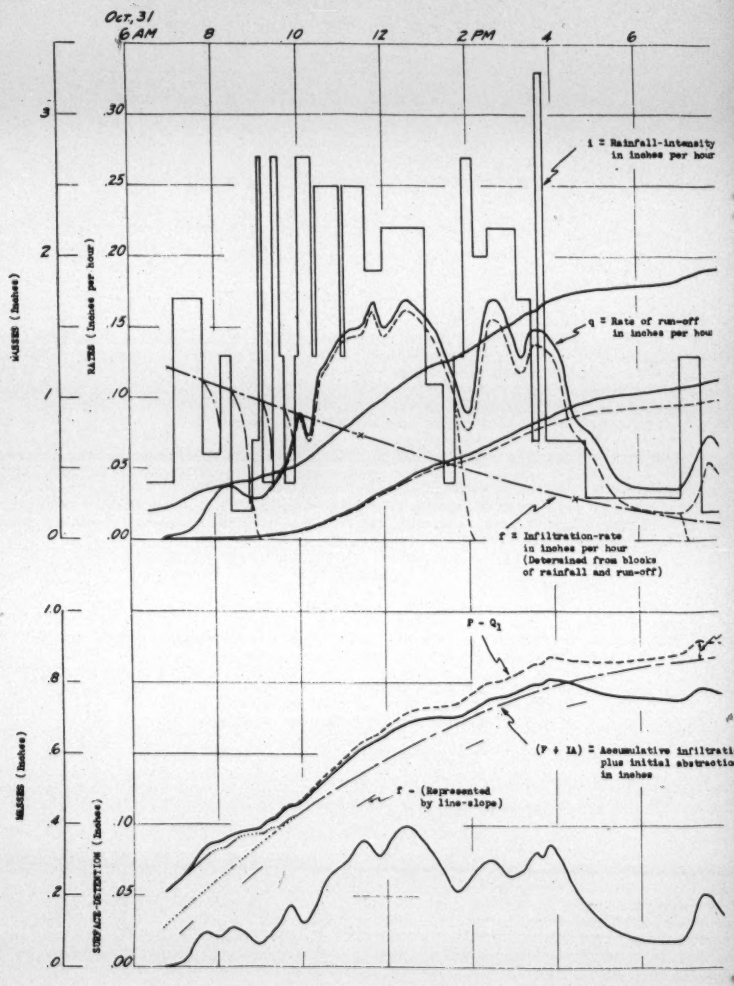
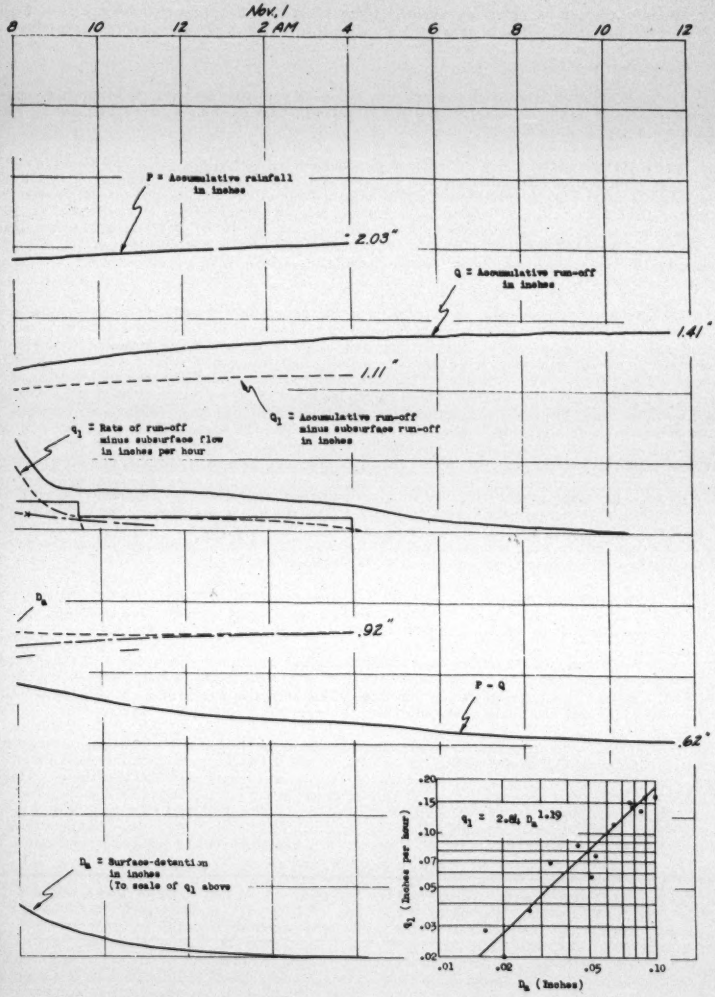

Oct, 31
6 AM
8
10
12
2 PM
4
6
i = Rainfall-intensity in inches per hour
q = Rate of run-off in inches per hour
f = Infiltration-rate in inches per hour (Determined from blocks of rainfall and run-off)
RAINS (inches per hour)
MASSES (Inches)
F - Q1
(F + IA) = Accumulative infiltration plus initial abstraction in inches
f = (Represented by line-slope)
SURFACE-DETENTION (Inches)

Fig. 1--Illustration of procedures used in determining the infiltration-curring on October 30, 31, and November 1, 1941, at the Soil Conserva-



rate on a small agricultural watershed for a storm-runoff period oc-
tion Experiment Station, Bethany, Missouri

The histogram of the storm and accompanying runoff from the watershed are plotted in Figure 1. The rate of rainfall, i, the accumulative rainfall, P, the rate of runoff, q, and the accumulative runoff, Q, comprise the basic data secured by actual measurement. Amount-values are in inches and rate-values in inches per hour.

The methods used in studying the data are of the rational type following the procedures suggested by HORNER [2], and SHARP and HOLTAN [3], with improvisions necessary to make a reasonable evaluation of the data at hand.

Runoff occurred after some ten hours of precipitation at intensities well below the infiltration-rate. During this time approximately 0.21 inch of rainfall was retained on the area. It is estimated that initial abstraction, IA, was almost wholly satisfied during this period, and that its amount was approximately 0.05 inch. Depression-storage would be only partially filled at the start of runoff because the area is not homogeneous in slope, soils, or row direction. The slow rise of the hydrograph for the first half hour indicates that only a part of the area is contributing runoff. After this preliminary rise, however, the watershed as a whole appears to make a good response to an increase in the rainfall-intensity.

The accumulative runoff was subtracted from the accumulative rainfall to secure a cumulative (P - Q)-curve in which all unmeasured variables are represented. This curve was determined and transposed to an expanded scale, by use of proportional dividers, to the lower half of Figure 1. The fact that this curve has a pronounced negative slope for a protracted interval toward the end of the runoff-period indicates that subsurface flow is present. An examination of the rate of runoff, q, during this period indicates that the rate of subsurface flow is approximately 0.02 inch per hour, as the rate of runoff is obviously sustained for too long a period to represent surface-detention. Visible flow to the drainage-ways normally ceases some 10 to 20 minutes following the cessation of rainfall. The term subsurface flow is used here to represent invisible flow to the drainage-ways through a relatively pervious layer of topsoil, underlain by a less pervious glacial till.

From a knowledge of the watershed it is estimated that subsurface flow started at about $9^h\,00^m$ a.m. on October 31 and increased uniformly until toward the end of the storm. The rate of runoff, q, was, therefore, adjusted from $9^h\,00^m$ a.m. to some 15 minutes after the end of rainfall on the basis of a uniform increase from zero to 0.02 inch per hour. The resulting rate of runoff-curve, q_1, is assumed to represent surface-runoff to the drainage-ways.

The accumulative amount of surface-runoff, Q_1, was determined from the estimated q_1-curve. The quantity $(Q - Q_1)$ represents the amount of runoff which had previously been infiltrated into the surface-soil and later appeared in the waterways or drainage-ways of the area.

The accumulative rainfall minus accumulative surface-runoff, $(P - Q_1)$, was next transferred to the lower portion of Figure 1. After subtracting subsurface-runoff, $(Q - Q_1)$, decreasing values of $(P - Q_1)$ did not occur during the latter portion of the storm as was the case in plotting $(P - Q)$. The quantity $(P - Q_1)$ now contains all immeasurable variables excepting subsurface flow.

At this point in the analysis, Horner's principle of determining points of average infiltration from corresponding blocks of precipitation and runoff was used. Three such points were determined using the adjusted rate of surface-runoff curve, q_1, to compute Q_1-blocks of runoff. This required some estimation in projecting the rate of runoff to zero at the end of the blocks. The block of precipitation from $8^h\,55^m$ a.m. to $1^h\,40^m$ p.m. on October 31 may be used to illustrate the procedure. The amount of rainfall during the period is 0.87 inch, which is readily procured from the accumulative rainfall-curve P. The amount of runoff, Q_1, within the boundaries of the projected q_1-curves at the beginning and ends of the rainfall-period of 4.58 hours is determined to be 0.53 inch by use of a planimeter. The total amount of infiltration is, therefore, 0.34 inch, which, when divided by the time-period in hours, gives an average infiltration-rate, f, of 0.074 inch per hour. This value is plotted on the chart at $11^h\,23^m$ a.m., or at the midpoint of the precipitation-period with respect to time. Two additional f-points were similarly determined for subsequent blocks of precipitation and runoff. The infiltration-rate, f, throughout the storm is approximated by sketching a line through such points. It will be noted that values of f would drop appreciably due to lack of supply during the time-interval from $7^h\,00^m$ to $10^h\,00^m$ a.m. on October 31, a condition for which compensation is later made. Values of f may, however, be considered to be less than the rainfall-rate, i, throughout the remainder of the storm.

Values from the f-curve, secured by Horner's method, were transferred to the lower portion of Figure 1 to assist in determining the position of a cumulative curve of infiltration and initial abstraction, (F + IA), which is used by Sharp and Holtan to determine infiltration and surface-

detention. This was accomplished by placing several slope-lines, representing the value of f, on the lower portion of the work-sheet. Since the (F + IA)-curve must merge with the (P - Q_1)-curve at the end of runoff and its slope should parallel the slope-values previously placed on the work-sheet, it is relatively simple to sketch the curve, as it must be placed at a definite location to fulfill the condition. The breaks in the march of infiltration-values, due to a lack of supply during the period from $7^h\ 00^m$ to $10^h\ 00^m$ a.m. on October 31, were used to adjust the (F + IA)-curve to a position tangent to the (P - Q_1)-curve at the time excess rainfall occurred.

Surface-detention, D_a, in inches, throughout the storm, was approximated by subtracting values of the (F + IA)-curve from the (P - Q_1)-curve. Values of D_a were transferred to an expanded scale on the lower portion of the work-sheet by the use of proportional dividers.

The most probable exponential relationship of the runoff-rate, q_1, to the amount of surface-detention, D_a, was determined by the method of least squares, after tabulating corresponding peaks and valleys from both curves. The resulting equation was $q_1 = 2.84\ D_a^{1.19}$, for which the value of the correlation-coefficient is 0.58, or above a value of 0.53 required for significance. Pairs of values from which the relationship was derived are plotted on Figure 1. Some irregularity in the relationship would be expected to result from inability to determine the rainfall-rate accurately for the low values common to the storm.

The hydrograph has been analyzed to the point where certain qualitative statements may be made. Of the 2.03 inches of measured rainfall, 0.62 inch was retained on the area. Estimating initial abstraction at 0.05 inch, approximately 0.87 inch was infiltrated into the soil. Of the total infiltrated into the soil, approximately 0.30 inch reappeared as runoff by subsurface flow to the drainage-ways. The equation $q_1 = 2.84\ D_a^{1.19}$ approximately represents the relationship of the rate of runoff in inches per hour to the amount of surface-detention in inches, for rates and amounts in excess of those comprising phenomena of subsurface flow.

The infiltration-rate decreased throughout the storm, from a value of 0.12 inch per hour at the initial time of rainfall-excess, to less than 0.01 inch per hour about 15 hours later. The large volume of runoff occurring from the storm is due mainly to a decline in the rate of infiltration.

The process of combining certain procedures for determining the infiltration-rate, as outlined by HORNER [2], and by SHARP and HOLTAN [3], and using one as a check against, and to assist in determining the other, is helpful in ascertaining approximate values of the infiltration-rate throughout a storm-period.

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DISCUSSION

HOWARD L. COOK (U. S. Department of Agriculture, Washington, D. C.)--The most important feature of this paper is the attempt to determine what part of the flood-runoff was derived from subsurface flood-flow, that is, from previously infiltrated water returning to the channel-system during the flood-period. This is the most difficult operation in the calculation of flood-runoff from thin-soiled watersheds and the author is to be commended for realizing its importance.

It is presumed that the author corrected his hydrograph for the effects of storage in the pool above the measuring device and that also he made sure that the measured head was not affected by deposition of sediment in the throat of the flume at the tail end of the runoff-period. The long tails on hydrographs for small areas are often caused by either of the above, or the two in combination.

The author states: "The fact that this curve [the mass-curve of (i - q)] has a pronounced negative slope toward the end of the runoff-period indicates that subsurface flow is present." The inference is that a negative slope, or at least a "pronounced" negative slope, of the mass (i - q)-curve is an indication of subsurface flow. But the slope of this curve becomes negative whenever the runoff-rate exceeds the rainfall-rate, and this happens whenever a lull in rain-intensity necessitates a decrease in depth of surface-detention. (A study of Figure 1 will show that q exceeded i in ten separate intervals during the storm, these intervals aggregating 78 per cent of the total period.) Obviously, then, a negative slope of the mass (i - q)-curve is not a criterion for the identification of subsurface runoff. It would only be possible to utilize the slope of this curve in detecting and evaluating subsurface flow if an independent measure of the rate of flow from surface-storage were available.

It is possible to conceive of several ways in which subsurface flow might be evaluated. But regardless of the approach it will invariably be found that additional and independent information must be introduced at some point in the process, for measurements of runoff-rate yield no information on the source of the runoff. One can no more evaluate subsurface flow from an analysis of the rainfall- and runoff-measurements alone than he can determine the dimensions of an irregular figure knowing only its area.

In justice to the author it must be pointed out that he does introduce additional information to the extent expressed in his statement: "From a knowledge of the watershed it is estimated that subsurface flow started at 9^{h} a.m. on October 31 and increased uniformly until toward the end of the storm." He fails to show, however, how a "knowledge of the watershed" enables him to make such an estimate. It can only be concluded, therefore, that he has not furnished what can properly be called a method of evaluating subsurface flood-runoff. It will be fairly clear, moreover, that a quantitative evaluation of subsurface flow can only be made if the "additional information" is of a quantitative nature.

At the present time it appears that the most promising method of evaluating subsurface flood-flow is to estimate surface-runoff independently by the use of infiltration-data and surface-storage data secured by studies of small areas yielding surface-runoff only. The subsurface portion of the flood-runoff is then determined by subtracting the estimated surface runoff from the measured total flood-runoff. It will be obvious that in the present stage of knowledge the errors in estimating surface-runoff will be large and that for this reason the method described can only be used when subsurface runoff constitutes a fairly large proportion of the total flood.

THE APPLICATION AND MEASUREMENT OF ARTIFICIAL RAINFALL ON TYPES FA AND F INFILTROMETERS

H. G. Wilm

Introduction

In field-use of the types FA and F infiltrometers, some difficulties have been experienced in the consistent and uniform application and accurate measurement of artificial precipitation. Because consequent inaccuracies in computed infiltration-rates seemed undesirably large, it was considered desirable to work out improvements in existing equipment and to test a number of methods for measuring rates of water applied with the improved instruments. Accordingly, studies were organized to accomplish three main objectives:

(1) To review all practical suggestions for the improvement of both instruments and to incorporate them into the existing infiltrometers so as to provide instruments as free as possible of ordinary inaccuracies in water-application

(2) To test the shape and stability of rainfall-patterns applied with the improved equipment and to estimate the effect of variations in plot-slope and rainfall-rate upon shape and stability of patterns

(3) To evaluate the merits and accuracy of several methods of measuring rates of rainfall, and to show how the accuracy of selected methods is affected by variations in plot-slope, rainfall-rate, and other factors

The experiments described herein were done with the efficient aid of LOWELL WOODWARD and BERT C. GOODELL of the Intermountain Forest and Range Experiment Station. Complete reports, with descriptions of all instruments and procedures, are on file at the Division of Forest Influences of the Forest Service at Washington, D. C., at the Rocky Mountain Forest and Range

Experiment Station at Fort Collins, Colorado, and at the Intermountain Forest and Range Experiment Station at Ogden, Utah.

Equipment and experimental conditions

Hydraulic laboratory--All experiments were conducted indoors, in the hydraulic laboratory of Colorado State College, Fort Collins, Colorado. Ample space was provided in a large walled-in area with an adequately drained concrete floor. The whole area was amply protected from air-disturbances, so that no special protection had to be used. Air-temperatures varied between 50° and 70°F during the whole period of study, and rarely fluctuated over 10° during any single experiment. Fort Collins city water was circulated through the infiltrometers from a floor-pit; about every third day of tests the whole system was cleaned and flushed out, and the pit was refilled with fresh water. This water is unusually pure, with a mineral content of about 42 parts per million, of which about 17 are calcium carbonate [p. 487, Yearbook of the State of Colorado, 1939-40]. Water-temperatures varied from 44° to 57°F during the studies; the maximum range in any single experiment was about 7° and the average about 4°.

Infiltrometers--The instruments and accessories used in the experiments were assembled after considerable discussion and consideration of suggestions obtained from a number of sources. It should be emphasized that the results of these experiments apply strictly to this particular type of equipment, and that any great deviations from the recommended specifications may result in different--perhaps lowered--accuracy of rainfall-application and measurement. Below are summarized briefly the principal ways in which the Fort Collins infiltrometers may have differed from those in current field-use.

Type-Fa infiltrometer--The Jaeger pump ordinarily employed for the type-F instrument was used for supplying artificial rainfall, as the standard type-FA pumping equipment is known to have insufficient capacity to maintain uniform delivery of water. A five-gallon surge-tank was placed in the feed-line from the pump; flow to the pressure-gage and sprinklers was further regulated by a double valve, with a globe valve for coarse flow-regulation and a needle-valve for fine adjustment. No water-meter was used, as it seems quite generally agreed that discharge through a meter is poorly correlated with variations in rainfall applied to the infiltrometer. The sprinkler-nozzles were mounted on a rigid frame which, when properly levelled, placed the nozzles automatically and accurately at their proper position and angle (Fig. 1). (On steep slopes this frame requires an additional cross-piece, resting on the ground below and across the apex of the base triangle, in order to provide additional stability.) The plot-frame was a one-piece unit, 12 by 30 inches in dimensions.

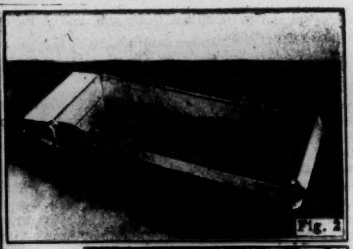
Type-F infiltrometer--The pump was a four-cylinder Pacific Marine pump, employed because the standard Jaeger pump is too low in capacity to provide uniform delivery of water to this large infiltrometer. A five-gallon surge-tank was installed in the feed-line. Twenty-six sprinkler-nozzles were mounted on a rigid, but portable frame, with a stop-cock below each nozzle for rapid changes in rainfall-intensity (Figs. 3 and 4). When the applicator-frame was installed over the plot, every nozzle was automatically and accurately placed at its proper position and angle. A new type of runoff-trough was employed, with its drain-pipe arranged to facilitate the weighing of runoff. Runoff-water was measured by weight, on a springless balance accurate to 0.1 pound.

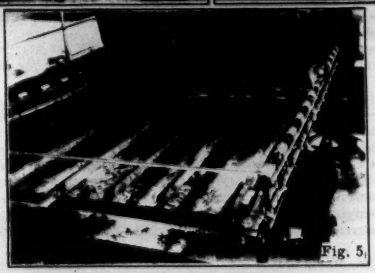
Each of the instruments and its sprinkler-frame were mounted on strong wooden frames, designed to facilitate changing plot-slopes (Fig. 3). On each frame, the downhill-end of the plot was 18 to 20 inches above the floor.

With all equipment in good condition, with pure water, small variations in temperature, and complete protection from wind, with the equipment moved between runs only as much as necessary to change plot-slopes, and with trained and careful personnel, the precision of these experiments was probably greater than that ordinarily experienced in field-surveys. Relative comparisons between methods of measuring rainfall should, however, be entirely valid; and data on the errors of the various methods should be fairly representative, since a distinct effort was made to simulate field-conditions which would be encountered with good equipment and a careful, experienced operating crew.

Design of the experiments

Formal studies--The experimental designs employed in these studies were chosen to measure all the desired comparisons and related effects in an unbiased manner, as efficiently as possible, and to provide data on experimental errors as nearly as possible like those encountered in infiltra-





Figs. 1-5

(1) Improved applicator-frame for type-FA infiltrometer
(2) Type-FA infiltrometer (new design) [On sloping ground the upper member (supporting the trough-gages) is moved uphill so that the rain-cutting edges at both ends are vertically above the plot-boundaries and the pivoted sheet-metal shield almost closes the front opening of the runoff-trough]
(3) General view of type-F infiltrometer in the hydraulic laboratory, with applicator-frame and two trough-gages in place
(4) Construction details of applicator-frame for type-F infiltrometer
(5) Type-F infiltrometer, with all five trough-gages in place

tion studies in the field. Each single observation of rainfall was exactly two minutes in length, so as to provide intervals similar to the one- and two-minute readings taken in field-studies, and long enough to minimize errors of timing. In most of the studies the two-minute observations were grouped into study-units about 1-1/2 hours in length, again so that variations encountered during a unit could resemble those experienced in an infiltration-test of average length.

These experiments were designed to test the following methods of measuring applied rainfall, each at plot-slopes of 5, 20, and 35 per cent:

Type-FA infiltrometer

(1) Two pans 12 by 30 inches in dimensions, one 1-1/2 inches and one three inches deep; with and without protection against splash-losses by a screen, baffle-grids, or both
(2) Ten cylindrical rain-cans, each 0.992 inch in top area, hung over the plot
(3) Trough rain-gages, 1 by 30 inches in dimensions, hung on each side of the infiltrometer (Fig. 2)

Type-F infiltrometer

(1) Waterproof tarpaulin hung over the plot-frame, with and without splash-protection by a coarse muslin screen
(2) Various combinations of two or three out of five trough rain-gages, each 1-1/2 inches by 12 feet in size, three over the plot and one along each side (Fig. 5)

Informal studies--In addition to the experiments discussed above, a number of studies were made which did not require formal design. Such tests included measurements of the amount of rainfall caught directly in the runoff-trough of the type-FA instrument, of losses by splashing from the type-F tarpaulin, and of rainfall-patterns as affected by factors such as plot-slope and rainfall-intensity on both instruments.

General experimental procedures

With all equipment ready for any desired test, the pump was started and water circulated through the sprinklers until the equipment was saturated and pressures and runoff-temperatures were stable. Then two-minute samples were taken of the runoff from the plot and rain-gages--collector-cans were moved under the drain-spouts and removed after two minutes, at signals from a note-taker equipped with a stop-watch. During each test one man attended the control-valves, keeping the water-pressure exactly at the prescribed number of pounds. Most of the time pressures were pleasingly uniform, requiring little regulation by use of the valves. Runoff-temperatures were read and recorded at the end of each two-minute interval. Between intervals, rainfall-rates were changed as called for in each design, by opening or closing nozzle stop-cocks and regulating pressures without stopping the motor. When data were grouped by complete sets as in a randomized-block study, or when plot-slope had to be changed, the motor was stopped between complete runs. In changing slopes the whole equipment had to be moved around almost enough to simulate moving from one site to another in the field.

For the type-FA infiltrometer all data on rainfall caught in the pans or rain-gages were recorded in cc, using graduates of appropriate capacities from 25 to 1,000 cc. Rain-gage data for the type-F infiltrometer were recorded in cc. Tarpaulin-runoff was measured by weight to the nearest 0.1 pound. These data were converted in the office to rates in inches per hour on the projected area of the infiltrometer. Before and after the experiments with each type of pan or rain-gage, the exact surface-areas of the pans or gages were obtained by careful measurements.

Results and conclusions

Type-FA infiltrometer--(1) With the recommended equipment, rainfall-volume and pattern-shape are regulated with satisfactory accuracy, even on different plot-slopes and at different rates of artificial rainfall. Water-pressures can be kept without difficulty at the prescribed number of pounds. The position, height, and angle of the nozzles are accurately controlled by a new sprinkler frame. In a newly designed infiltrometer-frame (Fig. 2), errors due to splash and to rain falling directly into the runoff-trough are minimized.

The rainfall-pattern is centered over the plot when the nozzles are mounted 30 inches above the soil and four inches away from the infiltrometer-frame, and tilted toward it at an angle of 4° In the other plane the nozzles should be kept vertical--not normal to the plot-slope; this is accomplished simply by mounting each nozzle in a street-ell.

(2) The use of a pair of trough rain-gages (each one inch by 30 inches), hung outside the plot, for sampling rainfall should be at least as accurate as the standard method using ten-minute readings before and after an infiltration-run. Under laboratory conditions the two methods are of equal accuracy; the reliability of the trough-gages, however, is little affected by wide changes in water-pressure, nozzle-slope, or other factors, whereas the error of the other method should vary directly with any reductions in precision of operating technique.

(3) A single 10-minute reading taken before or after an infiltration-run provides estimates of rainfall much less accurate than either trough-gage data or the use of both initial and terminal readings.

(4) Ten cylindrical rain-cans fail to provide a sufficiently accurate sample of rainfall; the error of their average is significantly greater than the errors of either of the two recommended methods.

(5) With either of the two best methods (pan or trough-gage readings), under optimum conditions a standard deviation expressing the variation of any single two-minute reading from the true rainfall should be about ± 0.08 to 0.13 inch per hour at any plot-slope or rain-intensity. Thus about one reading out of 20 will deviate from the true rainfall by ± 0.16 to ± 0.26 inch per hour. This amount of error is associated with uncontrollable, short-period variations in rainfall applied to the plot. Even though initial and terminal readings may be identical, intermediate readings (per two minutes) may vary over a considerable range and even with the water-pressures held exactly at 15 pounds.

(6) If initial and terminal pan-readings are used, the pan should be protected against splash-losses. In a pan three inches deep, such protection is adequately furnished by either a screen or a baffle-grid; in a 1-1/2 inch pan complete protection is provided by a combination of screen and baffles. An unprotected 1-1/2 inch pan will lose about 15 to 20 per cent of applied rainfall; a three-inch pan without splash-protection will lose up to ten per cent.

Type-F infiltrometer--(1) If the recommended specifications for this equipment and its use are followed, rainfall can be controlled with satisfactory accuracy, and its distribution and volume are relatively unaffected by large changes in plot-slope. (a) The tarpaulin and plot should be protected against splash-losses, especially on steep slopes, by means of a coarse muslin or wire screen. (b) Rainfall and runoff-volumes may be accurately and rapidly measured by weight.

(2) Ten-minute initial and terminal readings on a screened tarpaulin provide the most accurate method of estimating rainfall applied during an infiltration-test, and either initial or terminal readings alone seem to be just as accurate as the use of both together. These conclusions may apply only if the field-technique is at least as precise as our laboratory technique. Under experimental conditions the standard deviation of the difference between the estimated and true rainfall per two-minute interval is about ± 0.06 to ± 0.08 inch per hour--somewhat lower than the corresponding error for the type-FA infiltrometer. The smaller error is probably associated more with plot-size and number of nozzles than with the higher water-pressure.

(3) Of three combinations of trough-gages which were tested, the best results seem to be provided by two gages hung just outside the longitudinal boundaries of the plot. Under laboratory conditions the error of this or any of the other trough-gages is somewhat larger than that associated with tarpaulin-readings. In the field, however, the trough-gages may often prove to be the most reliable method of estimating rainfall on the plot.

In considering the results of these studies, the reader may wonder whether the unavoidable errors of even the best of equipment and methods of measuring rainfall are undesirably large, also whether they would constitute an important part of the experimental error of any infiltration-study. This question may be worth a little discussion.

Field-data have shown that in general the coefficient of variation of a single average minimum infiltration-capacity (f_c) in any single cover-type will vary between 25 and 60 per cent of the average f_c-value for the type. Assuming that it will average 40 per cent of an average f_c-value of 0.50 inch per hour, the variance expressing this variation is 0.0400--that is, the square of ± 0.20 inch per hour. Now, if each f_c-value were based on the final 12 minutes of each infiltration-run and if the standard deviation of single two-minute rainfall-measurements is about ± 0.12 per hour, then a variance expressing the error of the average rainfall is about $0.0024 - [(0.12)^2/6]$--about six per cent of the variance of the f_c-values. This amount is so small that it would certainly not be worth while to attempt its reduction by further improvement of instrumental techniques, unless such improvements required less than six per cent additional investment in equipment and time of personnel.

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DISCUSSION

DONALD A. PARSONS (Soil Conservation Service, Auburn, Alabama)--The privilege of discussing Dr. Wilm's paper for inclusion in the Transactions is welcomed for several reasons. It provides an opportunity to give a brief statement of the history of the development of these devices, and the objectives in mind during the development of each. Published recognition will finally be given the man who had most to do with the intimate details of their creation. Recent observations relative to the operation of the type-F apparatus will be related, and several points within the paper will be discussed.

In September, 1936, Dr. W. C. LOWDERMILK instructed the group of Soil Conservation Service workers at the Hydraulic Laboratory of the National Bureau of Standards to construct a suitable sprinkling-apparatus for simulation of rainfall on experimental plots of areas of 200 or 300 square feet. This group was under the general supervision of H. L. COOK and was a part of the Soil and Water Conservation Investigations Section, headed by G. W. MUSGRAVE.

We all realized at that time that our knowledge was insufficient to recognize a suitable sprinkling-device if we saw one, let alone create and construct one. Since urgent need was expressed for usable devices, the work was divided into three phases. The first phase involved the selection and reproduction of the apparatus then in use that appeared to have the most desirable characteristics. Accordingly, the apparatus described by C. KENNETH PEARSE of the Intermountain Forest and Range Experiment Station, Ogden, Utah, in "Specifications for the construction and operation of a portable apparatus for measuring surficial runoff and erosion" (March, 1936) was constructed. This apparatus was designated type-A artificial-rainfall apparatus in our laboratory series of experimental devices. Type F and type FA are the sixth and seventh, respectively, in the series.

The second and third phases of the work were carried out concurrently, each phase giving support to the other. One included studies of drop-sizes and fall-velocities in natural rain, determination of fall-velocities of water-drops at different heights of fall, and comparative tests for erosion and infiltration, using sprays of differing qualities. This work was briefly described in an article entitled "Recent studies in raindrops and erosion" by J. OTIS LAWS [Agric. Eng., v. 21, No. 11, November, 1940]. Another product of this study is the paper "The relation of raindrop-size to intensity", which is included in these Transactions [pp. 452-460].

The concurrent phase involved simultaneous work of construction and test on several newly conceived devices. Type B employed Skinner-ST50 nozzles. It was created, and later used in the field, by V. J. PALMER and H. N. HOLTAN. Type C was used only in the laboratory in the comparative tests of erosion and infiltration. It was called the "dripolator" or "stalactometer" type, employing a horizontal sheet of muslin with many short, vertical strands of yarn hanging from the lower side to convert a uniformly distributed fine spray above the cloth into large drops which formed and fell from the tips of the strands.

The type-D apparatus was developed by F. W. BLAISDELL after trying dozens of commercial spray-nozzles to find one that best suited the objectives. The objectives were to have a fairly large-drop spray, fairly evenly distributed, produced by a device that was the ultimate in regard to portability and ease of construction and operation. The Grinnell 1.5 "Mulsifyre" nozzle was employed. This apparatus, or modifications of it, has been used at the Virginia Agricultural Experiment Station and by E. L. BEUTNER and R. R. GAEBE at the Soil Conservation Experiment Station at Tucson, Arizona.

V. D. YOUNG, now at Fayetteville, Arkansas, produced the type-E apparatus. It employs a spray-nozzle that was developed by Mr. Young in the laboratory. This apparatus has been extensively used by H. L. BORST and RUSSELL WOODBURN at Zanesville, Ohio.

The type-F nozzle was also developed by Mr. Young in the laboratory, and he conducted the trials and experiments which resulted in the production of the device now known as the type-F artificial-rainfall apparatus. Thousands of painstaking, tedious measurements, and calculations were required in this work. His perseverance and skill made the development possible.

The associated work on raindrop-sizes and velocities had indicated the necessity of employing a spray composed of large drops. Therefore, the objectives in the development of the type-F apparatus were to provide a high-energy spray of low intensity, with the minimum possible spray-height, with drops falling nearly vertically at impact, and evenly distributed over at least a six-foot wide area.

The type-FA artificial-rainfall apparatus was produced in the fall of 1939 at the request of G. W. MUSGRAVE and R. A. HERTZLER of the then Flood-Survey Committee. The North Fork Infiltrometer had been extensively used during the summer by infiltration-survey parties. A change was desired in the type of spray but it was also desired to utilize as much of the equipment on hand as possible. This was done by using the type-F nozzle at pressure of 15 pounds per square inch.

Since drop-size and velocity are definitely known to affect infiltration and erosion if impact with bare soil occurs, it is quite important to consider the spray of an apparatus as being its prime distinguishing quality. Therefore, care should be used to differentiate between the results obtained with the type-F and type-FA apparatus. Although the same nozzle is used the pressures and heights of fall are different. The spray of the type-FA apparatus is composed of larger drops but they have lower velocities at impact with the plot. The spray of the North Fork Infiltrometer is widely different from either the type-F or type-FA sprays.

The tests by Dr. Wilm deal largely with the determination of application rates and the changes in the rate during the progress of tests. Our field experience with the type-FA apparatus has been practically nil, but we have had little difficulty with the type-F apparatus. When rate-changes occur they are probably due to one or more of the following reasons: Poor protection of the spray from air-currents; inadequate water-pressure control; partial clogging of nozzles due to inadequate screening of the water; or movement of some part of the applicator during the test. The magnitude of variations due to these causes is largely dependent upon the skill and alertness of the operators during erection and operation of the apparatus. A sturdier design for the applicator-support, as exemplified by that shown in the paper, should aid in regard to the last cause cited. The angle-iron support and sliding-hood features for the type-F apparatus were used by Mr. Musgrave's infiltration-party in the Concho Basin Survey in 1939

The splash-factor in the determination of application-rates has been recognized for some time. Mr. Musgrave's party in the work on the Tallahatchie Watershed used screens to prevent splashing during calibration. The original bill of materials for the type-F apparatus provided a tarpaulin for calibration that extended two feet beyond the side and top boundaries in order that splashing on to as well as off of the plot would occur. If splashing occurs over the end-sill during the infiltration-test, it should also be allowed to occur during the calibration. The converse is also true.

Another method of determination of application-rates has recently been used at Auburn. It avoids splashing difficulties and is particularly useful for plots with high vegetation. After the infiltration-rate has reached the point when a negligible change occurs in five or ten minutes, the application-rate is increased by uncovering or turning on a new set of nozzles. The resultant increase in runoff is the application-rate for the new set of nozzles. If the original set is now covered or turned off, the decrease in runoff-rate is equal to their application-rate.

Trough-gages along the sides of the plot may be useful to detect changes in application-rate during the progress of the test but they could hardly be expected to be a substitute for the measurement of application on the plot itself. PALMER and HOLTAN used this scheme with their type-B apparatus in 1938.

During the development of the type-F artificial-rainfall apparatus, tests were made that indicated a need for a shift upslope of the applicator of one and two-thirds inches for each per cent of slope. WILM, WOODWARD, and GOODELL, in the report referred to in the paper, concluded that a shift of two and one-half inches for each per cent of slope is required. This difference is not negligible on steep slopes, and a compromise value of two inches is suggested for use pending the attainment of additional data.

The use of a stop-cock for each nozzle, except for the additional cost, may be a good feature for some work. Less water would be needed under some conditions. Instantaneous, measurable changes in application-rate, however, cannot be obtained when they are used. This is true because time is required to turn all the valves and, because of changing the water-use, the water-pressure on all the nozzles will change and require time for adjustment. Studies of sheet-flow, where the amounts of water on the plot-surface are calculated, require instantaneous application-rate changes.

The new applicator-frame for the type-FA apparatus looks substantial and good. Two or three spikes on the bottom to help hold it in position might be desirable. A change in inclination of the nozzle from 7° to 4°, as suggested in the report referred to, should not materially change the height of fall and velocity at impact of the spray-drops for this apparatus.

These artificial rainfall-devices have come to be the property of all of us who are using them. The originators have performed their service and it has become a matter of the past. The men of the Forest Service, the Flood Control Survey of the United States Department of Agriculture, the Soil Conservation Service, and others who have had to use them to obtain needed information have by so doing learned their limitations and weaknesses, and have incorporated in their particular instruments and techniques the needed changes.

In conclusion I wish to express the gratitude of those who had a hand in the original work for the careful manner in which this first serious effort to check up on the performance of these devices has been undertaken.

APPLICATION OF A GRAPHIC METHOD OF ANALYSIS TO HYDROGRAPHS OF RUNOFF-PLOTS OF VARIOUS LENGTHS

E. H. Kidder and H. N. Holtan

(This study is being conducted as a cooperative project between the Illinois Agricultural Experiment Station, Urbana, Illinois, and the Soil Conservation Service, Office of Research. The authors wish to express their appreciation to C. A. VAN DOREN, L. E. GARD, and others in the Soil Conservation Service, who have assisted in the collection of field-data, analysis of result, and preparation of manuscript.)

To determine the effect of length and percentage-slope on soil- and water-losses, the Soil Conservation Service installed equipment for recording rainfall and runoff from various lengths of plots on slopes of five and nine per cent at the Dixon Springs Experiment Station in Pope County, Illinois. The station is located in the loess area of the lower Mississippi, which area is unglaciated, badly eroded, and low in productivity. Plots are located on four different sites or locations. The slope of two sites is five per cent, and of the remaining two, nine per cent. Five individual plots of various lengths each 42 feet in width are located on each of the four sites. Two plots 35 feet in length and single plots 70, 140, and 210 feet in length are represented on each site. Recording equipment for measurement of runoff was installed in the summer of 1940 on one plot of each length on each site. All sites were equipped with one recording and two or more standard rain-gages. Runoff is measured by type-H and type-HS flumes equipped with water-stage recorders. A three-year crop rotation of corn, winter wheat (lespedeza seeding), and lespedeza was followed. The winter wheat and lespedeza stands were grazed.

The objectives of this analysis were to determine the adaptability of the graphic method of hydrograph-analysis to plots of various lengths and to determine the relationship between length of plot and infiltration during the progress of storms. Two storms, November 11, 1940, and July 3-4, 1941, were selected for analyses because of their similarity in pattern, duration, and antecedent soil-moisture conditions. The storm in November occurred during the season of low transpiration and was preceded by 0.80 inch of rainfall on November 5, 1940. The storm in July occurred during the season of high transpiration, but was preceded by 1.15 inches of rainfall of which 0.96 inch fell eight hours previous to the storm-period analyzed. Both storms are of sufficient magnitude to insure a near approach to constant rates of infiltration.

The hydrographs from only the plots on slope of nine per cent were analyzed in this report, but all lengths of plots represented on both sites were analyzed, which means analysis was made of hydrographs from duplicate plots of each length. The plots were in lespedeza during these two storms; this validates comparisons of results between storms as well as between duplicates. Since these sites are 1.5 miles apart, slight differences in rainfall-pattern existed between the two locations.

The analysis used in this paper was the method developed by SHARP and HOLTAN [see 1 of "References" at end of paper] for a type A-2 storm. A type A-2 rainstorm is characterized by intermittent rainfall of such a nature that runoff will proceed intermittently. The following symbols from Sharp and Holtan's method will be used in this analysis: P = mass-rainfall in inches; Q = mass-runoff in inches; F = mass-infiltration in inches; D_a = surface-detention in inches; V_d = depression-storage in inches; IA = initial abstractions minus depression-storage plus canopy-interception in inches; i = rate of rainfall in inches/hr; q = rate of surface-runoff in inches/hr; f = rate of infiltration in inches/hr; f_c = final constant rate of infiltration in inches/hr. This method essentially includes a system of checks and balances which rather definitely establishes the position of the mass infiltration-curve.

Using the storm of November 11, 1940, on the 70-foot plot, Site 2 (Fig. 1), as an example for the development of the analysis, the first step as indicated earlier is to reduce the data for P, Q, i, and q to graphic form. The next step is to substract and chart (P - Q)-values as the storm

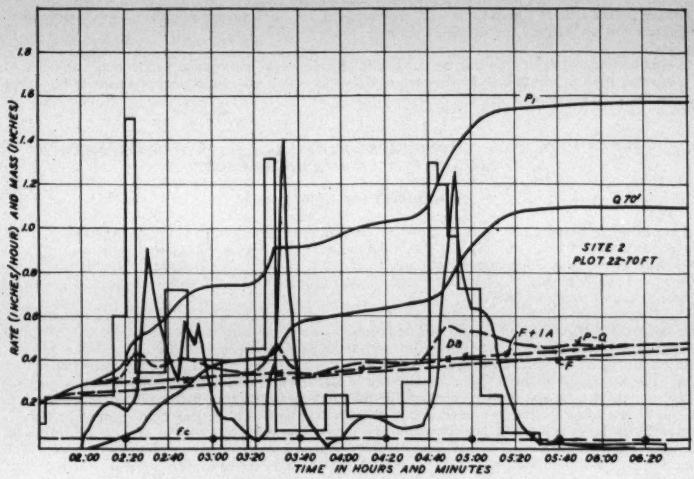

Fig. 1--Storm of November 11, 1940, Lespedeza cover

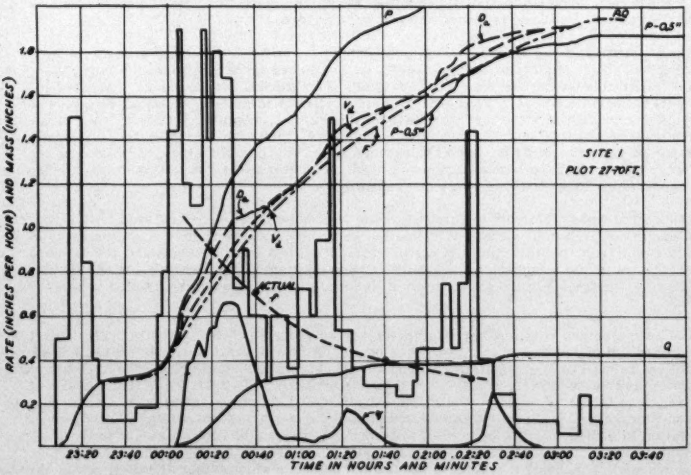

Fig. 2--Storm of July 3-4, 1941, Lespedeza cover

progresses, which gives a curve, (P - Q) = f(t), that is, (P - Q) as a function of time. Since, neglecting evaporation, P = (Q + F + IA + D_a) and (P - Q) = (F + IA + D_a), the (P - Q)-curve is then the (F + IA + D_a)-curve, from which a (F + IA)-curve can be deduced graphically, which enables one to evaluate D_a or detention.

To determine D_a a trial (F + IA)-curve is sketched in below the (F + IA + D_a)-curve. This (F + IA)-curve will approximately indicate a declining rate of infiltration in areas of rainfall-excess as the storm progresses until a constant rate of infiltration has been reached. For that part of the storm where runoff ceases, the (F + IA)-curve will be tangent to the (P - Q)-curve. These points of tangency assist in the placing of the curve in areas where runoff is taking place. Corresponding pairs of values of D_a and q were taken from the peaks, troughs, and recession-parts of the graph and plotted on logarithmic paper to establish a (D_a, q)-relationship curve (Fig. 3).

In the development of the (q, D_a)-relationship curve for the plots of various lengths it was found necessary to use a different (q, D_a)-curve for the 35-foot length of plot than for the 70-, 140-, and 210-foot lengths of plots (Fig. 3). In the formula for the relationship of q to D_a which takes the form of $q = a D_a^n$ where a = q when D_a = 1.0 and n = the slope of the (q - D_a)-curve when plotted on logarithmic paper, it is found that a = 228.0 and n = 2.23 for the 35-foot plot and a = 51.0 and n = 1.95 for the 70-, 140-, and 210-foot plots. This increase in the value of a for short plots is consistent with unpublished data collected from infiltration-studies at Edwardsville, Illinois. At this point these analyses departed slightly from the originally proposed method in that the "work-sheet" suggested in Sharp and Holtan's paper was eliminated and values of D_a (from Fig. 3) were subtracted from the (P - Q)-curve (Figs. 1 and 2) directly, and are not shown as additions to the Q-curve. This procedure was followed as a short cut and does not constitute a technical change. If the agreement is reasonably good, the resulting (F + IA)-curve is acceptable since variations in lag affect the (q, D_a)-relationship for different parts of the storm.

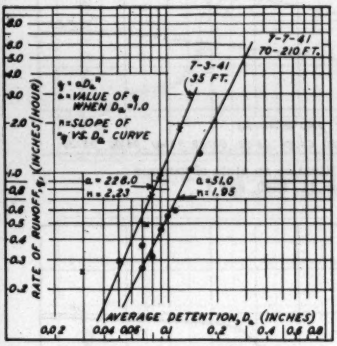

Fig. 3--Detention-runoff graph

The position of the F-curve is next established in areas of rainfall-excess by deducting an estimated initial abstraction from the (F + IA)-curve. These curves will be parallel except in areas where IA (mainly V_d) is decreasing or increasing. Where V_d and D_a are both depleted, the F- and (P - Q)-curves will be tangent. The F-curve like the P- and Q-curves cannot show decreased totals with time. The (F + IA)-curve will become tangent with (P - Q)-curve when runoff ceases and the F-curve will become tangent with the (P - Q)-curve when V_d is depleted. The position of the actual infiltration-rate curve can be determined by plotting values of f determined from the slope of the F-curve. The workability of this method is further demonstrated by its application to the storm of July 3-4, 1941, on a 70-foot plot (Fig. 2).

The (F + IA)-curve departs from the (P - Q)-curve at $12^h\ 01^m$ a.m. when runoff starts, but returns tangentially to it when runoff practically ends shortly before $1^h\ 00^m$ a.m. Increased rainfall shortly after $1^h\ 00^m$ a.m. causes D_a to rebuild and runoff to recur; in turn the (P - Q)- and (F + IA)-curves separate by the amount of D_a. These curves again become tangent at $1^h\ 55^m$ a.m. and remain so until $2^h\ 05^m$ a.m. when D_a is building up as indicated by runoff. The curves reunite at the final cessation of runoff. The F-curve is placed below the (F + IA)-curve a distance equal to V_d during periods of continued runoff; this allowance, estimated 0.02 to 0.05 inch, however, must be in line with the limitations imposed, namely, that the F- and the (F + IA)-curves must converge when V_d is depleting and must become tangent when V_d is exhausted. Convergence will occur around $1^h\ 00^m$ a.m. when V_d is being depleted and again around $2^h\ 00^m$ a.m., and the curves will join at $3^h\ 10^m$ a.m. when V_d is exhausted.

Discussion of results--Curves of mass-infiltration for the plots on each site during each storm were charted with the corresponding mass-rainfall for further analysis (Figs. 4, 5, 6, and 7). Mass-infiltration increased with increased length of plot on both sites for the storm of November

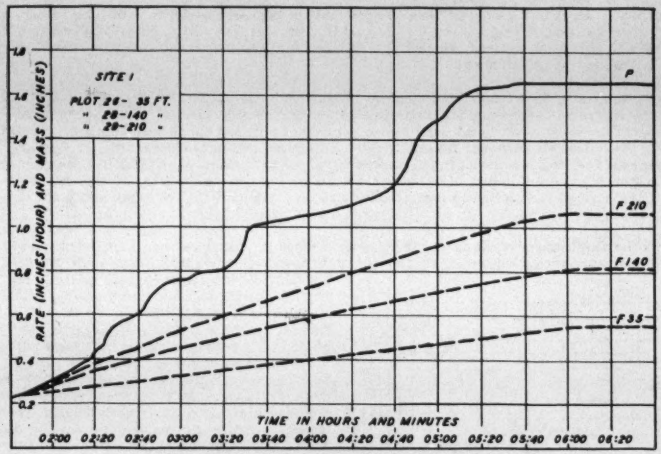

Fig. 4--Mass-rainfall and mass-infiltration on plots of various lengths, storm of November 11, 1940, site 1

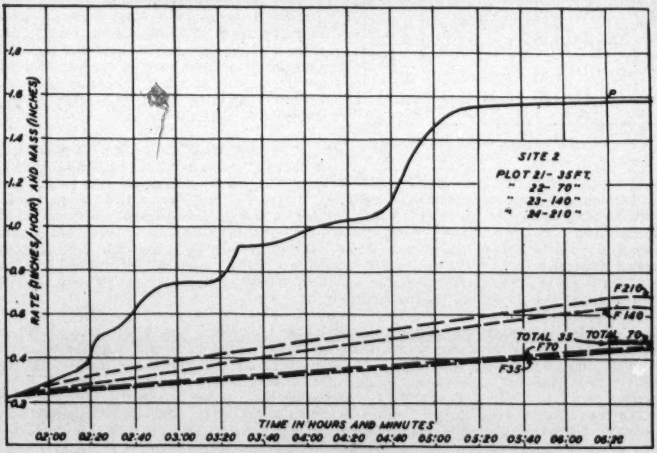

Fig. 5--Mass-rainfall and mass-infiltration on plots of various lengths, storm of November 11, 1940, site 2

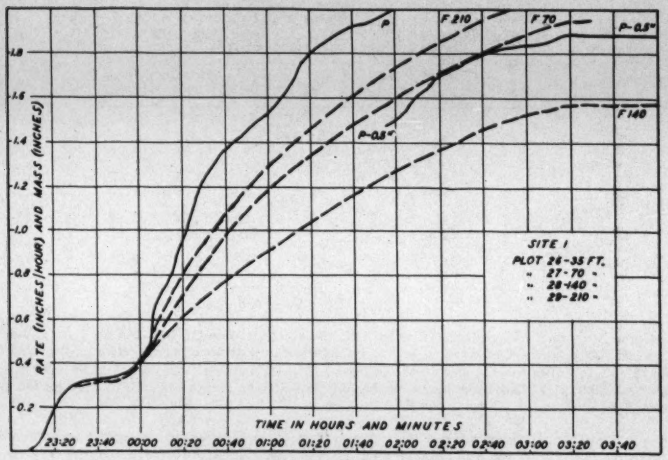

Fig. 6--Mass-rainfall and mass-infiltration on plots of various lengths, storm of July 3-4, 1941, site 1

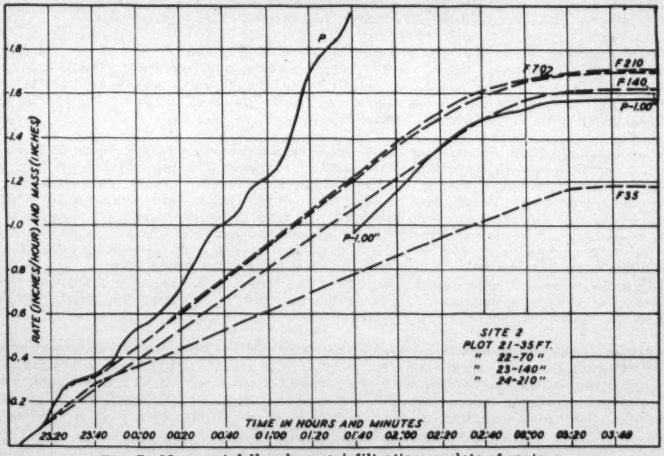

Fig. 7--Mass-rainfall and mass-infiltration on plots of various lengths, storm of July 3-4, 1941, site 2

Table 1--Total infiltration on plots of various lengths, two nine per cent slope-sites, for two rainstorms, Dixon Springs Experiment Station

Date	Site	Length plot	Infiltration	Date	Site	Length plot	Infiltration
1940		feet	inch	1941		feet	inch
Nov. 11	1	35	0.55	July 3-4	1	35	..... [b]
	2	35	0.48		2	35	1.18
	1	70	..... [a]		1	70	1.95
	2	70	0.49		2	70	1.70
	1	140	0.82		1	140	1.57
	2	140	0.64		2	140	1.62
	1	210	1.07		1	210	2.08
	2	210	0.69		2	210	1.72

[a]No record. [b]Flume silted, record discarded.

11, 1940 (no record on the 70-foot plot, Site 1). The mass-infiltration on 210-foot plot, Site 1, was 1.07 inches at $6^h\ 40^m$ a.m. as compared to a total infiltration of 0.82 inch on the 140-foot plot and 0.55 inch on the 35-foot plot for the same time-interval (Fig. 4, Table 1). On Site 2 at $6^h\ 40^m$ a.m., 0.69 inch of infiltration had taken place on the 210-foot plot as compared to 0.64 inch on the 140-foot plot, 0.49 inch on the 70-foot, and 0.48 inch on the 35-foot plot (Fig. 5, Table 1).

The mass-infiltration curves for the storm of July 3 and 4, however, do not show as consistent a trend as the curves for the storms of November 11, 1940. Total infiltration on the 210-foot plot, Site 1, was 2.08 inches as compared to 1.95 inches on the 70-foot plot and 1.57 inches on the 140-foot plot (Fig. 6, Table 1). On site 2, the greatest mass-infiltration of 1.72 inches took place on the 210-foot plot and the lowest total of 1.18 inches on the 35-foot plot. The total intake on the 70-foot and 140-foot plots was 1.70 and 1.62 inches, respectively (Fig. 7, Table 1).

Rates of infiltration as indicated by the slope of the mass-infiltration curves were lower in November, 1940, than in July, 1941, in spite of greater amounts of antecedent rainfall in July than in November. Others [2,3] have indicated that lower infiltration-rates may be expected in the fall and winter than in the summer. Temperatures ranging as low as 31° on November 10 may also have contributed to the low infiltration-rates in November.

Final rates of infiltration as interpreted from the mass-curve ranged between 0.09 and 0.19 inch per hour during the storm of November, 1940, and between 0.25 and 0.47 inch per hour during the storm of July, 1941 (Figs. 4, 5, 6, and 7). In consideration of the volume of antecedent rainfall prior to the storm of July, it again appears that summer infiltration-rates are probably higher than fall and winter rates. Percentage-infiltration derived from these two storms for the various lengths of plot cannot be considered indicative of the relative percentage total infiltration from rainfall for yearly periods, since a yearly record is made up of storms of varying intensities, total rainfall, and duration which together with varying soil- and temperature-conditions may or may not result in runoff for any one particular storm. Indications of infiltration for yearly periods from the various lengths of plot can be determined from a previous paper [4] by subtracting total runoff from total rainfall.

Summary--The hydrographs from various lengths of plot produced by two storms were analyzed by the graphic method of analysis. The purpose of this paper is to report preliminary analyses of hydrographs from one type of storm and with one cover-condition. This preliminary study justifies further testing of the graphic method of analysis on hydrographs from other types of storms with other cover-conditions as the data become available during the progress of the experiment.

On the basis of this analysis the total infiltration from the plots 210 feet in length was greater than from the plots 35 feet in length. Total infiltration from the plots 70 and 140 feet in length were intermediate in value but did not in all cases increase as the length of plot increased.

Infiltration-rates as determined from the slope of the mass-curves indicate that higher infiltration-rates occurred during the storm of July, 1941, than during the storm of November, 1940.

The analyses indicated good agreement between duplicate plots as reflected in the consistency of juxtaposition of F-curves within a given storm.

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Soil Conservation Service,
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DISCUSSION

KENNETH L. ROBERTS (U. S. Forest Service, Washington, D. C.)--The graphical procedure used by Messrs. Kidder and Holtan provides a simple and logical method of deriving the mass-infiltration curve and the progression-curve of infiltration-capacity from the mass-rainfall and the actual mass-runoff in areas where there is no appreciable subsurface flow during the storm.

The use of mass-curves in this graphical method shows clearly the correlated relations between rainfall, surface-detention, initial abstractions, infiltration, and runoff. For this reason it should be easy to check an analysis made by this method.

One difficulty that may be encountered in using the graphical method for the analysis of some data is that small errors in the slope of the mass-infiltration curve may cause relatively larger errors in the derived infiltration-rates. However, it is quite possible that infiltration-rates so derived would be as reliable as those derived from the same data by other methods.

If the method is applied to the analysis of a wide variety of data it would provide much useful information concerning the effects of such factors as length of slope, degree of slope, soil, and cover on the surface-detention, initial abstractions, infiltration, and runoff.

A PILOT STUDY OF GROUND-WATER RESOURCES IN PEORIA COUNTY, ILLINOIS

Max Suter

There are many ways of making ground-water investigations. Some lead to comprehensive results, others do not. In most cases the problem at hand will influence the approach and the final selection of the best method of procedure. Many factors are to be considered such as the time available, the existence or lack of available data and analysis, supply of technical personnel, financial support, and the attitude of local interests toward cooperation.

However, the efficiency of any investigation depends largely on careful planning. This cannot be emphasized enough. This planning should not lead to a rigid program, which is to be adhered to at any cost. The program must be revised from time to time according to the progress of the work, the results obtained, and the needs discovered for additional information.

This paper outlines the planning programs and methods used by the Illinois State Water Survey in its investigation of the ground-water resources of Peoria, the first of its large-scale studies of this kind. The method was designed to serve as a model for the solution of other similar problems with which the Survey is confronted.

Peoria is the second largest city in Illinois. In the metropolitan area, which includes Pekin,

there is a population of about 130,000. The district is highly industrial. Distilling and the manufacturing of machinery predominate. Although the Illinois River flows through the district, the water-supply is obtained exclusively from wells in the glacial drift. The total pumpage amounts to 70 to 90 million gallons per day, or an unusually large per capita consumption of 500 to 700 gallons per day. This enormous extraction naturally had to have a serious effect on the ground-water resources.

The Illinois River Valley at Peoria is about two miles wide. The hills on both sides are about 200 feet high. South of Peoria they are formed by carbonaceous rocks and shales with a light covering of glacial drift; north of Peoria they are mainly composed of glacial fill and drift, because the Wisconsin drift-sheet ended about at Peoria. Two rivers enter the Illinois Valley near Peoria, from the west the Kickapoo River, from the east, Farm Creek. Both of these rivers flow approximately along the northern edge of the hills formed by carbonaceous rocks.

The average rainfall is 34.88 inches, but it varies greatly. Using five-year sliding averages, long periods of slightly low rainfall alternate with short periods of high rainfall in about 21-year cycles.

The Illinois River water has a bad reputation as to its quality; the water from deep rock wells is salty and contains hydrogen sulfide, and therefore well water from the glacial drift has always been used as the only source of water.

Attention was first directed to the lowering of the water-level in 1936. At that time the Federal Government constructed a dam and lock in the Illinois River below Peoria. While the local people blamed the lowering on the large pumpage in the coffer-dams, which amounted to over 25 million gallons per day, the Government made an investigation and claimed that the interconnection between pumpage and the lowering of the water-level could not be proven.

Nothing further was done on the study of ground-water until 1940, when reports reached the State Water Survey through the National Resources Planning Board that certain industrial wells did go dry. In order to have a basis for further study, the Survey made an inventory of all wells from office records, publishing the results in Bulletin 33 of the State Water Survey. It was only in October, 1940, that plans were developed for a thorough field-study, on which work started in November, 1940.

The aim was to collect and analyze the data necessary to develop specific recommendations for remedial measures and to formulate proper legal regulatory measures for conservation of the ground-water resources.

The problem was therefore not one of locating new water-sources as the industries were already established and could not be moved. Ways had to be found to safeguard or increase the ground-water supply in places where it had been depleted by previous continuous overpumpage.

The plan evolved for this investigation contained the following points:

(1) Arrange for cooperation with all interested agencies and industries.
(2) Inspect all wells to determine: (a) Water-levels expressed with reference to mean sea-level; (b) pumpage and its variations; (c) which wells could be used for periodic readings to get long-time data.
(3) Search for abandoned wells on which automatic water-stage recorders could be installed.
(4) Make periodic analysis of water-samples from wells and the river to determine: (a) Interconnections between the waters; (b) long-time or periodic changes in the composition.
(5) Study the sources of ground-water, as from (a) precipitation and infiltration and (b) Illinois River and side creeks.
(6) Study of the geologic conditions.
(7) Establish the hydraulic gradients of the ground-water and map the ground-water contours.
(8) Study possibilities of artificial recharge.
(9) Combine all data to get a complete record of ground-water resources, their balance as to inflow, storage, and safe rate of continuous extraction.

This plan has proved to be very satisfactory. As the study progressed only a few points had to be added, such as:

(1) Bacterial analysis of the river-water to determine its value as the source of recharge-water.

(2) Study of the efficiency of cooling towers for use in recirculating systems as a method of reducing the pumpage from wells.
(3) Permeability-determinations on soil-samples from test-wells drilled on strategic locations by the State Water Survey.
(4) Measurements of ground-water velocities with the salt method.
(5) As additional help became available, it was necessary to prepare careful instructions covering the different observations to be made in order to get uniformly satisfactory results.

Of course, not all points on the program received the same degree of attention, but none was neglected. Some general remarks may be given here before discussing a few special problems.

Effective cooperation was obtained from all agencies. The National Resources Planning Board provided consulting services. The United States Engineers determined the altitudes of many wells and furnished readings from their own observation-wells and on river-stages. The United States Geological Survey installed an extra gaging-station on Kickapoo Creek. Rainfall- or temperature-data are being obtained from the Peoria Station of the United States Weather Bureau. The State Geological Survey prepared a topographic map of the bed-rock surface from well-logs and special resistivity surveys. The Soil Conservation Service is assisting in making infiltration-studies and the Illinois Agricultural Experiment Station mapped the infiltration-capacities of the soils northwest of Peoria. The Peoria Association of Commerce sponsored appropriations by the State Legislature, provided office space, and arranged public meetings for the discussion of the problem with locally interested persons. City offices and all industries cooperated by giving access to wells and records.

Important benefits were derived from the original decision to reduce all well- and surface-elevations to sea-level datum. This required that all wells be leveled in by special surveys. Taking the elevations from a topographic map was not a sufficiently exact method of determining gradients of the static ground-water level. The static water-level is defined here as that level to which the water rises in a single well after that well is shut down for a sufficiently long time to show no measurable rise in level. It is not the original static level to which the ground-water might rise if all the wells in the district would cease pumping for a long period, a level on which there are very few data.

It was considered that the single-well static level was the one giving the desired information on the water-resources, especially as to available water-storage, direction of flow, general recession or rise in ground-water levels, interferences between neighboring wells, and other pertinent factors. This level is also that shown in unused wells in the vicinity of the active wells. Many of these unused wells are equipped with water-stage recorders to give exact data on the movement of the water-level in the wells.

Weekly measurements are made on most of the active wells except during periods of floods, when attempts are made to get daily readings.

Care was taken to get a favorable geographical distribution of observation-wells over the whole area, with a denser concentration in places with steep gradients or in depressions of the ground-water surface. Where special observation-wells were needed, they were drilled by the State Water Survey and equipped with recording instruments.

Industrial wells are usually read by someone in the plant, under instruction and check-up by the staff of the State Water Survey. Although nothing is paid for this service, it cannot be considered as free. In the first place, the well owner should make these readings in any event for his own information; in the second place, the data are tabulated and graphed for the whole district and returned to him in a digested form. By having the wells read by the industrial plants themselves, not only is an educational work done in training the plants to keep important records, but also the interest in the investigation is kept constantly alive.

Little difficulty was found in getting the cooperation of the industrial plants. One well going dry naturally helps to teach many neighbors to watch their own well-levels. More difficulty was encountered from those well-drillers who were unwilling to install air-lines, which are considered by many of them as purely a nuisance. Convincing the well owner of the necessity of the air-lines and requiring the consulting engineers to prescribe them in the specifications are often the only recourses. Steps should even be taken to urge the manufacturers of pumps to provide better facilities for the installation of air-lines.

There are now 101 wells in the Peoria District on which data on ground-water elevations are

obtained. Of these, 25 are measured by the staff of the State Water Survey, including 11 equipped with water-stage recorders.

Data on exact pumpage are somewhat more difficult to obtain. Although approximate figures on pumpage are required from 115 places, only eight establishments are able to furnish monthly data on metered pumpage. These eight plants, however, pump 42 per cent of the total ground-water used in the district

The installation of meters is being fostered with little success under present priority restrictions. The lack of meters is really surprising, as only a measured supply can give the industry exact data on the cost of its water.

Routine systematic collection is now made for the following data: Well-levels; pumpage; river-stages and flow; temperature of well and river-water, dry and wet bulb of air; chemical composition; well-logs and soil-samples of all new wells; and rainfall.

With all the data collected only a few fully explicable solutions have been found. On the other hand, it seems that the more varied the observations made, the more unexpected are the relations discovered that are unexplainable by our commonly accepted theories. This compares with the well-known case of rain-gages; as long as only one rain-gage is set out, the feeling obtains that the amount of rainfall is exactly known. Yet as soon as several rain-gages are in use in a district it becomes clear that no exact amount of rainfall over the district can be determined. A few of these peculiarities will be mentioned.

Ground-water has been pumped along the river so much that it stands about 20 feet below the river-stage. All indications are that no river-water feeds the ground-water, as the bottom of the river is heavily silted. Owing to the regulatory navigation dam below Peoria, the water-level is kept at a constant pool-stage, rising above it only during heavy floods. During such floods it has been observed that the ground-water rises also, and that a rise of one foot in river-stage causes a rise of about one foot in the ground-water in the main pool and one of four feet in the north pool. This might be caused by infiltration from flooded areas; if so, then the ground-water level should continue to rise so long as these areas are flooded or until the ground-water level also stays constant. Furthermore, as soon as the river recedes, the ground-water recedes also, although its level is below the river. Where does the water go? An explanation might be found in the compressibility of the gravels. Special tests show, however, that even under the most favorable conditions this compressibility can account for a rise in the ground-water of only one inch for every foot of rise in the river. No satisfactory explanation is at present available for the data on these interrelated water-levels.

So long as well-water temperatures from only one well were available, they indicated clearly a lag of about five months in the temperatures. The well-water was the warmest in November and the coldest in May to June. The relation still holds in that one well, but in all the other wells now measured no such correlation can be found with any regularity.

The same general statement can be made about the chemical composition. The first data from one well indicated that in spring the water is harder, more alkaline, and contains more sulfates, whereas in autumn it is richer in chlorides. Systematic monthly analysis of 12 wells in the last two years, however, show no such regular variations, but the amount of change in composition is appalling. For example, hardness varies in one well from 460 to 765 parts per million; in another, from 320 to 545. Sulfates vary in single wells from 36 to 236 parts per million or from 56 to 160 parts per million. Such high proportional variations are found in total residue, alkalinity, chlorides, calcium, and magnesium.

What do these peculiar manifestations indicate? First of all, they give warning that no conclusions should be drawn from observations over only a short period and thereby serve as a stimulus to continue the systematic collection of data. Yet they also spur the invention of extraordinary explanations, which further tests should prove, modify, or disprove. In no case, however, should the facts be distorted to prove a well-meant theory. Often inability to find an explanation also leads to the initiation of additional tests, be they the same test on more wells or new types of tests. Often it is clearly a case of waiting for the effects of other combinations of natural processes. For example, floods are generally accompanied or preceded by heavy rains. It is then difficult to determine the effect of the flood in the river and that of the rain. If there should ever occur a flood without heavy local rains or heavy local rains without a measurable rise in the river, then it may be possible to arrive at an explanation.

For the present the plan and program can only prepare us to meet the situation when things begin to happen.

A few individual problems encountered during the study may deserve some special remarks.

Peoria Dam and Lock--There are many people in Peoria who blame the whole ground-water shortage in Peoria on the construction in 1936 of the dam of the United States Engineer Office across the Illinois River below the city. During that construction nearly ten billion gallons of water were removed from the coffer-dams at an average rate of over 25 million gallons per day.

An investigation was made at that time by the United States Army Engineers, which showed from geological evidence that this pumpage did not affect Peoria. Yet all the wells in Peoria that kept records showed a decided lowering in the water-level during that period of construction. Not enough careful measurements were made, however, to give convincing engineering evidence of the interaction, positive or negative. This whole problem is mentioned here because it shows clearly that ground-water problems must always be attacked from the viewpoint of many sciences, especially where quantitative and not only qualitative results are needed. It also shows that the lack of data taken during certain operating phases, in this case the construction, makes it practically impossible to evaluate the after-effects after cessation of the operating phase.

Infiltration-studies--In looking for the source of ground-water, the areas and rates of infiltration of rain and stream-water have to be defined. Geological studies must be made to determine qualitatively if the water passing through the soil can reach the district in which pumping occurs and hydrologic investigations have to measure, quantitatively, flow and storage available.

It was the purpose of the infiltration-tests to determine, and map, for the major soil-types in the area that are believed to furnish ground-water to Peoria the rates at which they will absorb water.

Several methods have been used to determine the infiltration-capacities of soils. None of these methods can exactly duplicate conditions as they occur in the field. Each method has some advantages and some disadvantages. Thus far, the cylinder method has been used in this project because it seemed to be the best method available of getting at fundamental or inherent soil-differences. It was felt that the first step should be to try to get some idea of the permeability of the different soil-profiles. Additional studies by some other method could determine the variations due to conditions of cover and surface of the soil. Additional studies should also determine effectiveness of different methods for increasing ground-water recharge--for example, types of planting, direction of plowing, and contour-farming. As yet no data seem to be available on the influence of these methods on the ground-water, mainly because the soil-agronomists seldom care what is going on below the grass-roots.

Geological studies--These were made to investigate the formations composing the glacial till and drift and to determine the topography of the bed-rock surface and the rock-formations composing it. All well-log records and many electrical-resistivity traverses were used.

In the course of this work a buried rock hill in Peoria and an old abandoned and filled-in valley to the west of Peoria were discovered. This valley was originally eroded deeper in the rock than the present Illinois River Valley.

Both these geological findings were earlier suspected from hydraulic observations.

Hydraulic studies--Many soil-samples from well-drilling operations have been subjected to permeability tests to get the range of this important soil-property. Special wells were drilled at four locations to determine the velocity and direction of the ground-water movement. For this purpose the wells were drilled at the corners of equilateral triangles with 50-foot sides. The salt-method was used for the determination of velocity and the direction was calculated from the difference in velocity in two directions. An electrical conductivity-cell was used for the detection of the salt-concentration.

The results of these tests vary greatly in reliability. They require much time and labor and give only approximate values. Determination of ground-water velocities by the use of dyes may be tried in the future.

Recharge-test--The steady lowering of the ground-water level indicates that more water is being pumped from the wells than is replaced by natural recharge. The amount of this lowering

allows the calculation of the over-pumpage--about five million gallons per day. The situation can be alleviated or remedied to some extent by pumping less, or by the use of artificial recharge, or both.

Reduction of pumpage in a very active industrial area such as Peoria can be obtained only by elimination of waste, by the use of recirculating-systems through cooling-towers, or by the use of river-water. All these methods are under study and legislation is under consideration to help to enforce such needed measures, which in some cases have already been adopted voluntarily.

Artificial recharge can be accomplished in three ways: (a) Through wells; (b) through large infiltration-pits; or (c) by land-flooding.

Infiltration through a well was tried in one place in Peoria, but the high iron-content of the aerated ground-water that was returned caused the well to become clogged in about one month. Well-drilling operations also showed that some wells, when filled with water, lose it only very slowly into the ground. Wells were therefore considered to be not a practical solution for the large-scale infiltration needed.

Considerable experimentation was done in an abandoned gravel-pit on the infiltration of river-water into the ground. The plan was to use the cold river-water during the winter for infiltration to build up the needed amount of storage for pumpage in summer. The test itself should furnish data on the practicability of the method, the rates of infiltration and a basis for design. Three test-wells were drilled around the pit and equipped with water-stage recorders, and a sampling apparatus was made available. Arrangements were made with the owners of 12 existing wells in the neighborhood for assistance in making readings of temperature and for taking samples for chemical and bacteriological examination. An idea of the extent of the test can be obtained when it is considered that during three test-periods a total of 27.8 million gallons were pumped into the pit at a rate of three million gallons per day. Most wells were sampled about hourly. In all, about 100 bacteriological samples were taken, more than 1,200 analyses for chlorides were made, and more than 1,000 measurements of temperatures recorded. The percolation of water out of the pit was studied by following the chloride-content after dissolving five tons of salt in the pit.

The test proved fully that this type of infiltration has practical possibilities. The rate of infiltration in the pit was determined to be 37 million gallons per day per acre of unprepared gravel-pit, indicating that at a rate of only ten million gallons per day per acre during the cold months of the year less than two acres of prepared pit-area are needed to fully satisfy the requirements of the industrial area of Peoria. The only difficulty was found in the spread of bacteriological contamination which could be followed for more than 420 feet, although all the water pumped into the pit was chlorinated.

A firm of consulting engineers was invited by the Peoria Association of Commerce to make a report on the feasibility and cost of artificial infiltration. These engineers recommended land-flooding by pumpage as a more economical practice, being cheaper in initial cost and using more available materials, although being somewhat higher in operating cost.

None of the proposed methods of artificial infiltration has been put into actual practice, mainly because of the hazard of incurring responsibility for pollution of the ground-water as defined in Illinois law.

Summary--The investigation that is being conducted by the Illinois State Water Survey on the ground-water resources at Peoria is described. This investigation is characterized by its careful planning and by the use of all branches of science that relate to ground-water phenomena. This required the coordination and cooperation of many agencies. The program and its modifications are given, the cooperating agencies are listed, some of the results are described, and many of the yet unsolved problems are discussed. It is shown that the many-sided attack on the problem uncovers many unexpected relations that cannot be explained by the commonly accepted theories, yet will lead to a new understanding and evaluation of fundamental principles.

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DISCUSSION

ADOLPH F. MEYER (Minneapolis, Minnesota)--The author shows good appreciation of the requirements of any study, irrespective of the specific field of investigation concerned--careful

planning, but without the establishment of an inflexible program and revision of procedure during progress of the work and in the light of data collected from time to time. That type of approach has general application. There may be emphasized something suggested later in the paper by the author, namely, continuous and intensive expert supervision and study of the data being collected with early "speculations," shall we say, as to possible cause and effect relationships, with a view to securing, from an early date, all basic and related information required for testing such "speculations." After an investigation has been completed a study of the data secured frequently discloses that some essential information was overlooked and some other information that was gathered has only meager value. Some phases of an investigation need usually be expanded and amplified; others may advantageously be abridged if intensive study proceeds parallel with the field-investigation.

The author raises a number of questions in his paper, but fails to give any information that permits the reader to hazard suggestions. The following running comments indicate matters respecting which the writer would like to have had information as he proceeded with the reading of the paper.

How deep are the wells? How thick is the drift? How far to ground-water? Where is the natural ground-water outlet located, or is there proof that the author is dealing with a closed basin? If so, what are its area and other physical characteristics?

Pumpage at a given rate may not "naturally have a serious effect on the ground-water resources." It may only produce the gradients required to cause the necessary flow of ground-water to the artificial outlet.

How deep are the rock-wells? Is there any interconnection between the ground-water in the drift and the water in the deep rock-wells? The writer has found surprising interconnections on several projects.

What was the level of the water in the sump of the Government coffer-dam with respect to the ground-water level in the adjacent region?

Is the ground-water level so far below the surface of the land that capillary effects due to temperature are limited to variable release of moisture held in the upper few feet of soil, and do not affect the ground-water level below through increased capillary lift? The writer has found surprisingly large hourly changes in high ground-water levels in peat-soil due to changes of temperature.

Is the ground-water level below the river-level both above and immediately below the Government dam?

Most streams are fed largely by ground-water, even when the "river bottom is heavily silted." Why, then, should there be no seepage-loss from rivers flowing above the ground-water level? Lakes in the vicinity of the Twin Cities in Minnesota, for which the writer has designed pumping-projects to maintain them, are losing substantial quantities of water through their bottoms. Here the ground-water level in the drift has been substantially lowered by pumping of artesian wells many miles away.

Is there no ground-water flow down the valley to answer the question of receding ground-water after floods? If the basin is closed the problem is greatly simplified.

What water-temperatures were found, and how do they compare with the mean annual air-temperatures in the vicinity? What annual water-temperature changes were observed?

Is the ground-water beyond the reach of vegetation? Have precipitation less evaporation and transpiration losses been computed? On one project the writer found a perfect correlation between ground-water level and precipitation minus losses.

What is the Illinois law respecting pollution of ground-water?

After further study of the paper it would seem to the writer that if the investigation has reached the stage where the over-pumpage has been definitely fixed at an average of five million gallons per day, then it would seem that the profession would greatly benefit by a presentation of the physical data upon which that conclusion was based. Certainly those data are intimately related to the practicability and desirability of various methods of artificial recharge.

MAX SUTER--Mr. Meyer raises many questions concerning exact data obtained and results achieved by the investigation. Sufficient data are on hand to answer most of these questions; but it should be borne in mind that the study is still going on, and our fund of information is being constantly augmented. For this reason any statement concerning final results would be premature.

Under the circumstances, the paper avoided too much factual emphasis and concentrated rather on the functional phases of the investigation in progress. The purpose was to outline the method of carefully planned attack which took into consideration all the sciences believed to have a bearing on the problem, and which made use of all possible cooperation. Considerable space was also devoted to showing how inconsistencies in the first tentative conclusions were revealed by a systematic study of all the facts. Most of these inconsistencies cannot be explained as yet, chiefly because of the shortness of the period of observation, but it is important to have discovered them as a guide for the future direction of the study.

PRELIMINARY REPORT ON ANALYSIS OF RUNOFF RESULTING FROM SIMULATED RAINFALL ON A PAVED PLOT

C. F. Izzard and M. T. Augustine

This paper deals with the preliminary results of analysis of runoff from a paved plot based on experimental data obtained in November, 1942, from a cooperative research-project of the Public Roads Administration of the Federal Works Agency and the Soil Conservation Service of the Department of Agriculture. The project was set up to obtain basic data on the hydraulics of overland flow from paved and turf-surfaces of the character normally encountered on landing-strips for aircraft.

The data here reported were obtained entirely on the initial series of runs on a relatively smooth surface. The second phase of the investigation, now under way, will be concerned with runoff from a rougher surface more nearly conforming to surface-conditions likely to be encountered in practice. The third phase will consist of measurement of runoff from a sod-surface laid on the same movable platform used for the earlier investigations. These three phases are more or less preliminary to the final objective, namely, accurate measurements of runoff and infiltration under field-conditions from turf-plots 12 to 72 feet long on grades of one to six per cent.

The cooperative research-project has been under the direction of the senior author, with the junior author in charge of the field-operations. G. W. MUSGRAVE, Research Specialist of the Soil Conservation Service, has served in a consulting capacity. The experimental work has been carried out entirely with standard infiltrometer-equipment of the Soil Conservation Service. Further details of the experimental set-up are given below and have also been described in a paper presented at the last annual meeting of the Highway Research Board [see 3 of "References" at end of paper].

Description of equipment and method of operation--The experimental data covered by this report were obtained from measurements of runoff occurring on a smoothly paved plot six feet wide by 72 feet long, the slope of which was varied from 0.1 per cent to two per cent. The surface of the plot had approximately the texture of a sheet-asphalt pavement and consisted of a mixture of emulsified asphalt and sand. Rainfall was simulated by means of type-F infiltrometers mounted along the full length of the 72-foot plot with nozzles 18 inches center to center. Water under pressure was conveyed separately to each 12-foot set of nozzles by means of rubber hoses connected to a fire hydrant. This hydrant was within 500-feet of an elevated storage-tank, and pressure remained substantially constant throughout all the runs. The hoods covering the nozzles were connected to levers in such a manner that either all or half of the nozzles could be opened or shut instantly. The actual rainfall-intensities varied from about 3.60 inches per hour to 4.10 inches per hour with all of the nozzles operating, and from 1.65 inches per hour to 2.02 inches per hour with half the nozzles operating. As far as could be determined, these differences in intensity took place between different runs rather than during a given run.

Runoff was measured by means of a type-HS flume, 0.4 foot wide, with head measured by a point-gage. The zero of the point-gage was determined by at least two observations made at the beginning of each run. Discharge was read and recorded at ten-second intervals, except on the lower end of the recession-curve, when the rate of discharge was changing so slowly that 30-second or 60-second intervals were satisfactory. The hydrographs plot substantially as smooth curves, indicating that the point-gage readings were carefully made. The temperature of the water discharged from the flume was read at least once during each run. Temperatures during the series of tests varied from about 9° to 15° C.

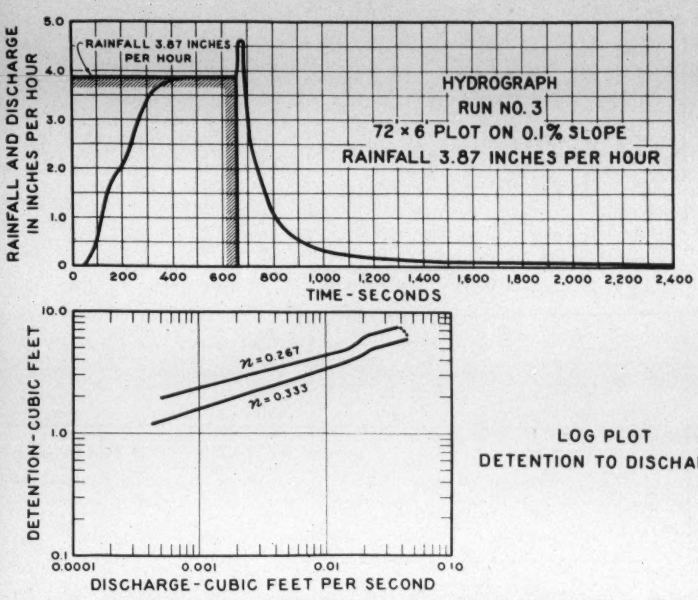
RAINFALL AND DISCHARGE IN INCHES PER HOUR
RAINFALL 3.87 INCHES PER HOUR
HYDROGRAPH
RUN NO. 3
72' × 6' PLOT ON 0.1% SLOPE
RAINFALL 3.87 INCHES PER HOUR
TIME - SECONDS
DETENTION - CUBIC FEET
n = 0.267
n = 0.333
DISCHARGE - CUBIC FEET PER SECOND
LOG PLOT
DETENTION TO DISCHARGE

Fig. 1--Typical hydrograph and detention versus discharge curve for runoff from 72-foot plot on grade of 0.1 per cent with rainfall of 3.87 in/hr

Corrections were made for pondage according to the standard method used by the Soil Conservation Service. A plot of the uncorrected discharge-readings compared with the corrected readings shows a difference in volume of water about equal to the amount of water held back in the flume at the equilibrium-stage.

The runs were made on grades 0.1, 0.5, one, and two per cent. At each of these slopes the general procedure was to make two runs at each of the two rainfall-intensities for a plot 72 feet long. Then, by blocking off successive portions of the upper end of the plot, similar runs were made on plots 48, 24, and 12 feet long. The usual procedure was to permit discharge to build up to the equilibrium-stage and to continue rainfall for five to ten minutes, or in any event long enough to be certain that the mean rate of rainfall could be determined with reasonable accuracy. The discharge-readings were taken on the recession until the discharge was reduced to approximately 0.05 inch per hour. The water remaining on the plot was then swept off and weighed.

On the flatter grades, several pairs of runs were made involving two rainfall-intensities. One series of runs was also made with rainfall stopped before discharge had reached the equilibrium-stage.

The hydrographs were plotted to scale of one inch = 0.5 inch per hour as ordinate and one inch = 100 seconds as abscissa. It was found that the total area under the hydrograph, by planimeter, plus volume of water swept off, checked the computed volume of rainfall usually within less than one per cent. In no case did the apparent error exceed three per cent. The volume of water under the recession-curve plus volume swept off usually checked closely the volume of detention as measured above the rising side of the hydrograph. Typical hydrographs are shown in Figures 1 to 4.

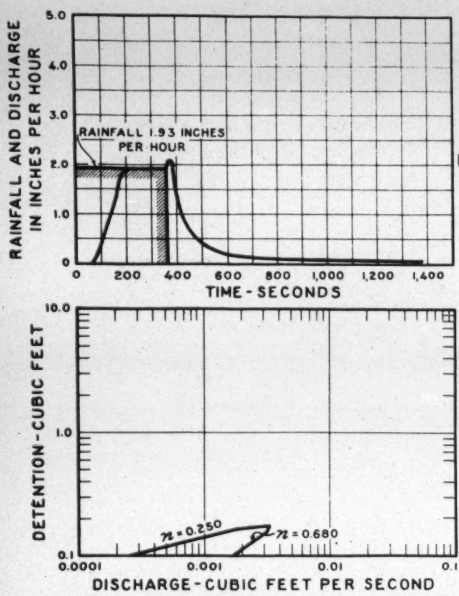

Fig. 2--Typical hydrograph and detention versus discharge curve for runoff from 12-foot plot on grade of 2 per cent with rainfall of 1.93 in/hr

Tests were conducted on grades of one and two per cent with conditions of steady uniform flow obtained by permitting water to enter the upper end of the plot over a series of baffles at rates maintained constant while depth-measurements were made at the lower end of the plot. Depths were measured by means of two point-gages located at the quarter points of the width, approximately two feet from the end of the plot.

Analysis of data--A preliminary analysis of the data was made by plotting total detention on a unit-width of plot against length of plot for each rate of rainfall and each slope. These data indicated generally that for a given rate of rainfall and a given slope, the detention was proportional to the length of the plot to the four-thirds' power. The proportionality-constant was found to be a function of the square root of the rate of rainfall divided by the slope to the three-tenths' power. These relationships were found to be approximately correct in the more detailed analysis which follows. The preliminary data indicated that the surface-profile was parabolic with the average depth approximately three-fourths of the depth at the end of the plot.

The next step in the analysis was to compute the volume of detention at ten-second intervals throughout the entire hydrograph, except where the rate of discharge was changing slowly. These computations were made for runs representative of each rate of rainfall, slope, and length. Detention was plotted logarithmically against discharge (see Figs. 5 and 6). It was found that the data plotted as straight lines over practically the entire length of the rising side of the hydrograph and at a different slope for the falling or recession-side of the hydrograph, except for the short interval of time immediately after rainfall ceased, when the flow was adjusting itself to the new condition. Invariably the amount of detention necessary to maintain a given rate of discharge was less during recession than on the rising side of the hydrograph. On all runs a sudden momentary increase in discharge was observed immediately after rainfall had ceased. Analysis of the data

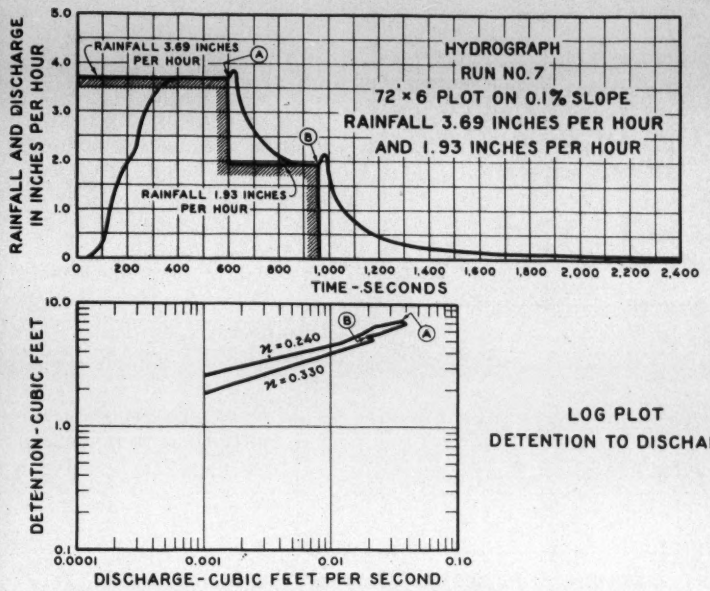
RAINFALL AND DISCHARGE IN INCHES PER HOUR
RAINFALL 3.69 INCHES PER HOUR
HYDROGRAPH
RUN NO. 7
72' × 6' PLOT ON 0.1% SLOPE
RAINFALL 3.69 INCHES PER HOUR
AND 1.93 INCHES PER HOUR
RAINFALL 1.93 INCHES PER HOUR
TIME - SECONDS
DETENTION - CUBIC FEET
n = 0.240
n = 0.330
DISCHARGE - CUBIC FEET PER SECOND
LOG PLOT
DETENTION TO DISCHARGE

Fig. 3--Typical hydrograph and detention versus discharge curve for runoff from 72-foot plot on grade of 0.1 per cent with rainfall-rate of 3.69 decreased to 1.93 in/hr

and comparison of derived surface-profiles show that this increase in the rate of discharge was due to the discharge of the quantity of water necessary to provide additional head to overcome the resistance caused by the impact of raindrops on the sheet-flow.

As noted by HORTON [1], the basic relationship between detention and discharge can be represented by an equation of the form

$$D = K q^n \qquad (1)$$

(For symbols used, see Table 1.)

In Figure 5, logarithmic plots of detention against discharge for the rising side of the hydrograph resulting from simulated rainfall of 1.8± inches per hour are combined for 16 runs representative of the entire range of tests at this rainfall-rate. It will be observed that throughout the range of discharge from 0.001 cubic foot per second to 0.04 cubic foot per second the slope of these curves is substantially constant. The curves for the 12-foot plots are the least consistent, as can be expected from the difficulty involved in obtaining accurate discharge-measurements in this range. The curves generally have a steeper slope below Q = 0.001, but from a practical standpoint this difference is immaterial.

Since the actual rates of rainfall of the separate runs varied, it was necessary to make a correction to reduce the data to a common rate of 1.8 inches per hour. This was done by using the previously established approximate relationship that detention is proportional to rainfall to the one-half power. A line having this slope was drawn through the upper end of the plotted curve (that is, the equilibrium-point). The point of intersection of this line with the uniform rate of

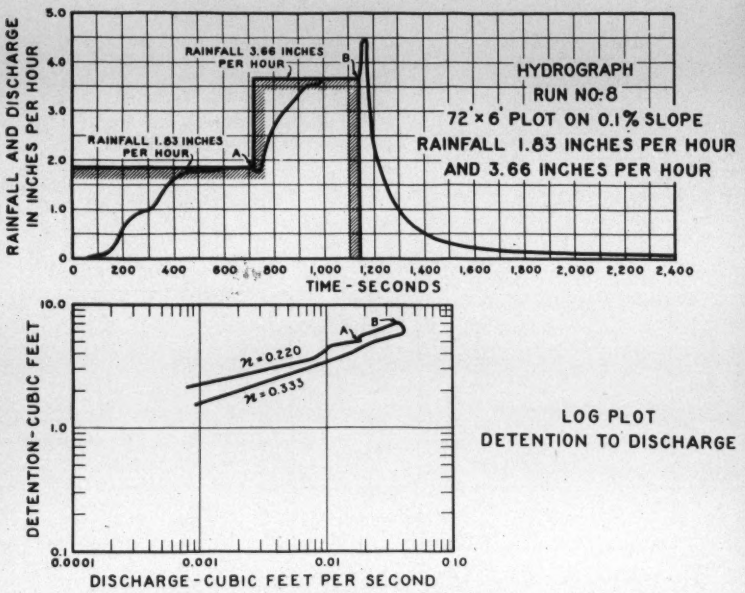

Fig. 4--Typical hydrograph and detention versus discharge curve for runoff from 72-foot plot on grade of 0.1 per cent with rainfall-rate of 1.83 increased to 3.66 in/hr

Table 1--Notation

Symbol	Unit	Definition
L	feet	Length of plot
ℓ	feet	Distance from upper end of plot
s		Slope of plot
D	$feet^3$	Detention on unit-width of plot
D_e	$feet^3$	Detention on unit-width of plot at equilibrium
d	feet	Depth of flow at point ℓ, or at outlet
d_a	feet	Average depth = (D/L)
ℓ_0	feet	Distance from upper end of plot at which slope of energy-gradient becomes substantially constant for flow at equilibrium
p	inches/hour	Rate of rainfall
Q	$feet^3$/second	Rate of discharge from plot of length L having width of six feet = 6q
q	$feet^3$/second	Rate of discharge on unit-width = ($p\ell$/43560) at equilibrium
v	feet/second	Velocity at point ℓ
K		Proportionality-constant = ($6D/Q^n$)
K_r, K_f		Proportionality-constants on rising and falling sides of hydrograph, respectively = (D/q^n)
n		Exponent of q in equation $D = Kq^n$
m		Ratio of outlet-depth to average depth = (d/d_a)

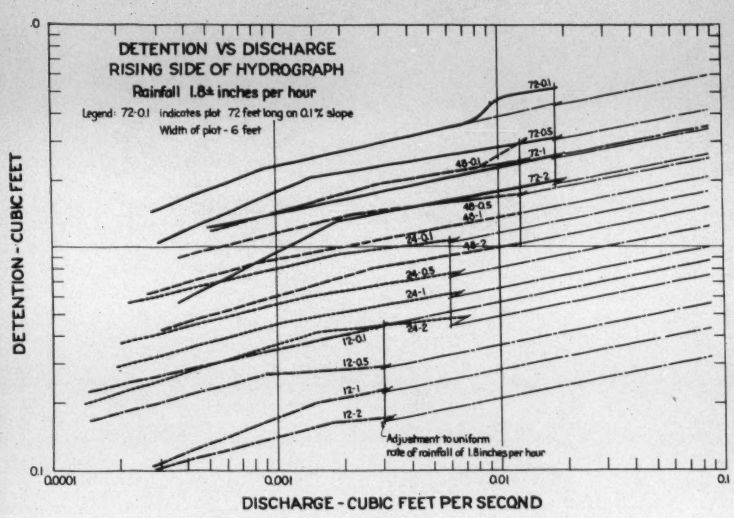

Fig. 5--Combined logarithmic plots of detention versus discharge on rising side of hydrograph for rainfall-rate of 1.8+ in/hr

rainfall, reduced to cubic feet per second for the respective length, was then taken as the equilibrium-point for the corrected curve.

A slope of 0.2 was found to most nearly fit all the curves for the rising hydrograph, including those for a rainfall-rate of 3.9 inches per hour. Lines on this slope were extended through the corrected equilibrium-points to intersection with the abscissa Q = 1, thus determining the intercept K.

This intercept K was then plotted against length of plot L to determine the second intercept, which was then plotted against slopes.

A similar procedure was followed for the rising hydrographs of runs resulting from rains of 3.9± inches per hour. This enabled determination of the effect of rainfall-rate p upon the coefficient K. The approximate equation finally derived is

$$6\,D = K\,Q^{0.2} \tag{2}$$

in which

$$K = (p^{0.34}\,L^{1.10}/103\,s^{0.3}) \tag{2a}$$

As might be expected, the logarithmic plots of detention against discharge on the recession-side of the hydrograph, reproduced in Figure 6, practically coincide in so far as the effect of rainfall-rate is concerned, after the initial surge of excess-detention has been discharged. The equation fitting these curves approximately over the entire range tested is

$$6\,D = K\,Q^{0.375} \tag{3}$$

in which

$$K = (LQ^{0.375}/30.8\,s^{0.3}) \tag{3a}$$

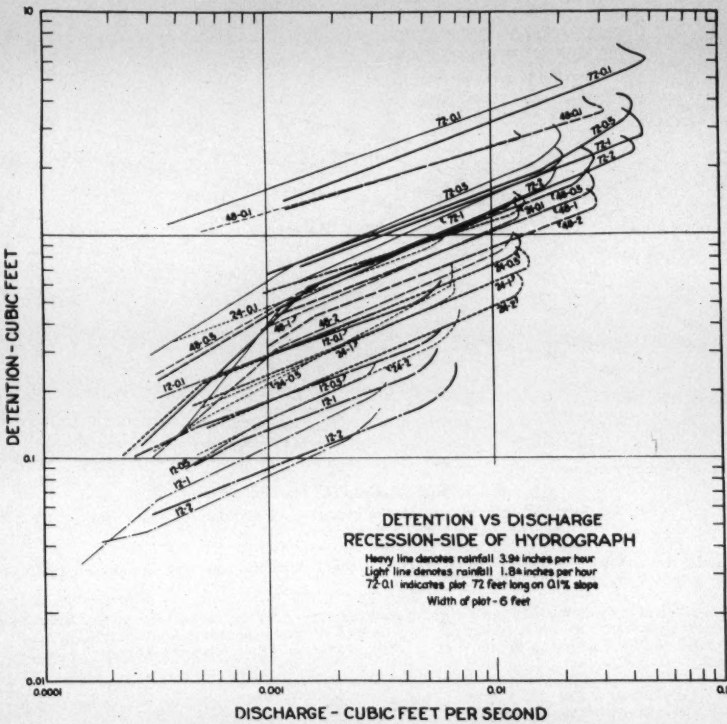

Fig. 6--Combined logarithmic plots of detention versus discharge on recession-side of hydrograph for rainfall-rates of 3.9± and 1.8± in/hr

Actually the exponent in this case varied from about 0.33 to 0.42, the value selected being an approximate average for which convenient power-tables are available [2]. Investigation of the effect of this exponent on the synthesis of the recession-hydrograph sustains HORTON'S contention [4] that the form of the hydrograph is relatively insensitive to minor variations in this exponent. Study as to the reasons for this variation, which may be correlated with slope of the plot, have not been completed.

The foregoing equations have dealt with the discharge Q on the six-foot width of plot. For convenience all subsequent equations will deal with discharge and detention on a unit-width of strip.

The basic equation for detention on the rising side of the hydrograph for a unit-width of plot is

$$D = K_r\, q^{0.2} \tag{4}$$

in which

$$K = (p^{0.34}\, L^{1.10}/432\, s^{0.3}) \tag{4a}$$

The detention on a strip of unit-width is equal to the area under the surface-profile. Therefore

$$D = \int_0^L dd\ell \tag{5}$$

At equilibrium D becomes D_e by notation and q = (pL/43560), converting discharge in inches per hour to cubic feet per second. Substituting in equation (5)

$$D_e = (p^{0.54} L^{1.30}/3670\ s^{0.3}) \tag{6}$$

Differentiating D_e with respect to L

$$(dD_e/dL) = (1.30\ p^{0.54} L^{0.30}/3670\ s^{0.3}) = d$$

Thus

$$d = (p^{0.54} L^{0.30}/2820\ s^{0.30}) \tag{7}$$

Also

$$d = (m\ D_e/L) \tag{8}$$

in which m = exponent of L in equation (6). Since $(d_e/L) = d_a$, then m also equals the ratio (d/d_a), or the ratio of outlet-depth to average depth.

Equation (7) becomes the equation of the surface-profile if we change L to ℓ, the latter symbol being used to denote the distance from the upper end of the plot. Profiles computed by this equation were compared with surface-profiles based on the outlet-depth of plots 12, 24, 48, and 72 feet long, respectively. The outlet-depth was computed from detention at equilibrium using equation (8). The agreement was good on grades of one and two per cent and fairly good on the grade of 0.5 per cent. Since the basic equation (4a) did not take into consideration the increased detention caused by the hump in the curves in Figure 1 on the grade of 0.1 per cent, the computed profile fell somewhat below the points computed from actual detention-values on this grade. From the standpoint of overland flow on landing-strips, the divergence on the grade of 0.1 per cent is immaterial since it is impractical to construct any kind of a pavement on that flat a grade.

The fact that surface-profiles derived from the basic-flow equation check closely with those developed from measured volumes of detention is evidence that the outlet-depth is not appreciably affected by the overfall at the outlet. Over the major range of tests the depth of flow near the outlet is above the critical (that is, $(d/2) > v^2/2g$), but since flow is not uniform, the computation of a draw-down curve would be complex, if it could be done at all. Further study of this problem may be undertaken.

By substituting L = (43560 q/p) in equation (7) we get

$$d = (p^{0.24}/115\ s^{0.3})\ q^{0.3} \tag{9}$$

$$q = [7.28\ (10^6)\ s\ d^{3.33}/p^{0.80}] \tag{10}$$

$$v = [7.28\ (10^6)\ s\ d^{2.33}/p^{0.80}] \tag{11}$$

Since v = (q/d) = (p/43560d), velocity can be expressed in terms of length ℓ, using equation (7) for d

$$v = (p^{0.46} s^{0.30}/15.5)\ \ell^{0.70} \tag{12}$$

The basic equation for detention on the recession-side of the hydrograph for a unit-width of plot is

$$D = K_f\ q^{0.375} \tag{13}$$

in which

$$K_f = (L/94.5\ s^{0.3}) \tag{13a}$$

Note in comparison with equation (4a) for the rising side of the hydrograph, that the factor p (rate of rainfall) has dropped out, and the exponent of L has changed to unity. Equation (13) applies to that portion of the recession-curve for which the detention-discharge curve plots as a straight line on logarithmic paper. A systematic means of reproducing the transition from equation (4) to equation (13) has not been fully developed.

The average depth of flow of the recession is

$$d_a = (D/L) = (q^{0.375}/94.5\ s^{0.3}) \tag{14}$$

Since there is no equilibrium-point on the recession-curve, it is not mathematically correct to differentiate to determine the equation of the surface-profile as was done on the rising side of the hydrograph. By analogy, however, it seems reasonable to assume that the ratio m of outlet-depth to average depth is (1 + n), since in this case the exponent of L in equation (13) is unity. This assumption is in accord with HORTON'S analysis [1].

We then have $d = 1.375\ d_a$ or

$$d = (q^{0.375}/68.7\ s^{0.3}) \tag{15}$$

$$q = (68.7\ s^{0.3}\ d)^{2.67} = 7.93\ (10^4)\ s^{0.8}\ d^{2.67} \tag{16}$$

$$v = 7.93\ (10^4)\ s^{0.8}\ d^{1.67} \tag{17}$$

Equation (17) coincides almost exactly with the velocity-depth relationship for depths of flow up to 0.007± foot derived from steady uniform flow previously described. The same tests further indicate that flow closely follows MANNING'S formula (n = 0.011) for depths greater than 0.007 foot on the grade of one per cent. The transition-zone on the grade of two per cent is poorly defined but the points approach the same formula at a depth of 0.013 foot. The experimental data are insufficient to warrant any precise definition of the lower limit of turbulent flow.

Mathematically the flow for depths less than 0.007 foot as determined by both uniform steady-flow tests and by analysis of the recession-hydrographs as represented by equation (17) is not laminar since the exponents of slope and depth, respectively, should be one and two for laminar flow. The indications are that flow does approach the laminar type on the slope of 0.1 per cent. Further studies of the data already available and additional experiments are needed before any conclusions are warranted with respect to the existence of laminar flow. The fact remains that equation (17) closely describes flow on the recession-curve throughout the entire range of conditions embraced by this series of experiments.

In so far as the data have been analyzed to date, there does not appear to be any definite correlation between temperature of water and velocity.

Critical depth--Using actual values of D_e, adjusted to uniform rainfall-rates of 3.90 and 1.90 inches per hour, respectively, outlet-depths d at equilibrium were computed by equation (8) for each of the four lengths of plot and the four slopes. Mean velocity $v = (q/d)$, velocity-head $(v^2/2g)$, energy-head $(d + v^2/2g)$, and ratio of velocity-head to depth $(v^2/2gd)$, were then computed and plotted against length.

These curves revealed that flow passes through the critical depth as defined by the criterion $(v^2/2g) = (d/2)$ within the range of conditions tested. It was noted that discharge-readings were characteristically unstable when flow was at or close to critical depth. On the grade of 0.5 per cent, 72-foot plot, it was found that because of flow in the critical range, about 40 per cent of the total detention drained off in the same relative length of time required to drain the same relative quantity off with the plot on grade of one per cent. This phenomenon explained what had previously been thought to be a poor run.

The most significant fact developed was that the profile of depth plus velocity-head, or energy-head, is substantially a straight line beyond a point which can be mathematically defined by taking the second derivative of the energy-head with respect to length of plot. The transition-point so derived is defined by the following equation:

$$\ell_0 = 0.238\ p^{-0.345}\ s^{-0.82} \tag{18}$$

and has been computed for the range of conditions tested as shown in Table 2.

Table 2

p	s	ℓ_o (Computed)	ℓ_o (From graph)
3.9	0.001	43	48
	0.005	12	12
	0.01	6.5	10
	0.02	3.7	10
1.9	0.001	55	50
	0.005	15	18
	0.01	8.0	12
	0.02	4.7	10

The computed values derived mathematically from the basic equations (4) and (4a) check quite closely with points plotted from observed data by the method described above.

Additional studies will be made on energy-losses throughout the entire range of the tests, particularly with respect to the changes in momentum immediately following the instant that rainfall ceases.

Synthesis of the hydrograph--A graphic method of synthesizing the entire hydrograph resulting from a given rainfall-pattern is in process of development, utilizing the mass-curves of rainfall and runoff and the detention-equations (4) and (13) as tools.

Conclusions--The writers wish to emphasize that the quantitative data here presented are subject to revision after more exhaustive studies have been completed on all of the observed data. Because of the consistency of the data thus far analyzed, and the important implications and new conceptions derived therefrom, it has been considered desirable to present this preliminary report.

Unquestionably the most important concept developed as a result of this investigation is the fact that detention on the rising side of the hydrograph, or at any time that rain is falling, is definitely and appreciably greater than the detention required to maintain the same rate of flow on the recession-side of the hydrograph after all rainfall has ceased.

The basic equations should not be applied for lengths of overland flow greater than 100 feet, rainfall-rates greater than four inches per hour, or slopes steeper than two per cent, except with the implicit understanding that the type of flow may change sufficiently to cause an appreciable error.

This initial series of experiments were run on a relatively smooth surface conforming accurately to a plane. Surfaces of rougher texture and less accurate conformity will probably have greater values of detention for the same rate of discharge than those computed by the equations here derived.

References

[1] ROBERT E. HORTON, Surface runoff phenomena, Part I: Analysis of the hydrograph, Pub. 101, Horton Hydrol. Lab., February, 1935.
[2] HORACE W. KING, Handbook of hydraulics, McGraw-Hill Book Company, 1939.
[3] CARL F. IZZARD, Runoff from flight strips, Proc. 22nd Ann. Meeting Highway Res. Board, December, 1942.
[4] ROBERT E. HORTON, The interpretation and application of runoff plat experiments with reference to soil erosion problems, Proc. Soil Sci. Soc. Amer., v. 8, 1938.

Federal Works Agency,
Public Roads Administration,
Washington 25, D. C.

DISCUSSION

W. W. HORNER (Horner and Shifrin, Consulting Engineers, St. Louis, Missouri)--Our interest and much of our conception of overland flow goes back to Dr. Horton's presentation of eight years ago.

Since that time the studies of the Soil Conservation Service have provided some usable information with respect to flow over soils with various covers; in the last few years, the design of airport-drainage has produced a pressing need for better knowledge of flow over relatively smooth impervious surfaces. Mr. Izzard's data and analysis is therefore important and immediately useful in engineering practice.

He gives us values of mass-detention for four lengths of flow, four slopes, and two rates of rainfall, and complete hydrographs, from which an attempt may be made to determine the surface-profile and character of flow.

He has actually proceeded with an analysis of the data in considerable detail. I have had an opportunity to study the data and to look over his work-sheets. The data are unusually complete and accurate. To any one with an avid interest in hydromechanics it is a gold mine of information. Mr. Izzard has evidently been overcome by a natural curiosity and an urge to unravel it completely, and his notes suggest the burning of gallons of midnight oil.

Since it was impracticable to measure actual flow-depths, the analysis must be based on values of mass-detention for each length and slope. The relation between mass-detention and discharge at the lower end of the plot for the rising side of the hydrograph is given in the author's equations (4) and (4a). These equations may be transposed into the more usual form approximately as follows:

$$q = 2100\ S\ d_a^{3.33} \qquad \text{for } p = 2$$

$$q = 1210\ S\ d_a^{3.33} \qquad \text{for } p = 4$$

The writer using Mr. Izzard's original data for the equilibrium-points only, and without correcting for the exact rainfall-rates, made a similar logarithmic plot resulting in the following equations

$$q = 1110\ S\ d_a^{3} \qquad \text{for } p = 2$$

$$q = 770\ S\ d_a^{3} \qquad \text{for } p = 4$$

Undoubtedly Mr. Izzard's equation will fit the corrected data somewhat more accurately than the simpler form which the writer secured. It is extremely interesting that if the surface-profile is assumed to be a parabola with the mean depth equal to three-fourths of the outlet-depth then the fundamental equations for laminar flow at 15°C would be $q = 1180\ S\ d_a^3$. Also, Mr. Izzard's notes indicate Reynolds numbers for the flatter grades as of the order of 200 to 600. Mr. Izzard advises, however, that other tests do not seem to confirm the idea of laminar flow. It is to be hoped that he can give this matter of character of flow some further discussion in his closure.

The above equations present the relation between mass-detention and outlet-discharge, but do not of themselves give any clue to the character of the surface-profile for any particular length of plot. Mr. Izzard's further analysis appears to be based on the assumption that these equations also represent the relation between mass-detention and discharge above any point in the length of a specific plot. The use of this assumption leads to interesting results which are presented in equations (7) to (12). The writer would like to raise the question of propriety of the assumption and of equation (7) in particular. This equation indicates that at the upper end of the plot the depth must be zero. The writer's previous experience in applying the energy-equation to the flow in extremely flat channels indicates that this is not generally the case. The balance of forces and resistance is such as to commonly produce back-water at the upper end of such channels and a positive depth at that point. The question raised may be only of academic interest but might receive some consideration in connection with further analysis. It does not affect the practical value of the relationships established in equations (4) and (4a). The writer would also desire to raise the question about the effect of the occurrence of critical depth on this analysis. He has found as Mr. Izzard states in his paper, that the data fall on both sides of the critical flow-depth. On the grade of two per cent the flow is largely in the rapid field while on the one-tenth grade it is largely tranquil. It generally passes through the critical depth somewhere along the flow-path. Therefore, it would seem that the resulting mass-detentions do not constitute a homogeneous series of values and their relation to discharge cannot be satisfactorily represented by single equation.

Mr. Izzard's studies of specific energy and momentum are extremely interesting and indicate that the data might permit the analysis of the manner of dissipation of the rain-energy and the laws of change in flow-character over a range of rainfall-intensities; for this, however, another set of runs at lower intensity would be helpful.

A part of the rain-impact evidently acts to produce a super-elevation of the water-surface between raindrop-craters; this results in a reduction of width and an increase in depth and an actual increase in mass-detention. As he shows, on cessation of the rain the excess water passes off as a flood-wave.

It is to be hoped that Mr. Izzard can continue his analysis into some of the more involved phases, and ultimately satisfy our curiosity as to the mechanics of dissipation of energy. Both the practicing engineers and the field of hydraulic research owe him a vote of thanks.

CLARENCE S. JARVIS (Hydraulic Engineer, Washington, D. C.)--For those who have known something of the behavior of runoff from paved or roofed or other relatively impervious surfaces, the first question that naturally suggests itself is, "Will such experiments in simulated rainfall and resulting runoff be worth while?" Now that the series of tests have been so painstakingly conducted, analyzed, and reported to this assembly, the answer is surely in the affirmative. The very fact that the runoff and applied or simulated rainfall-rates become equal, after the preliminary detention-storage has been supplied, and that the recession-curve is of such a form as to extend the period of discharge in accordance with what would be expected, provides confirmation of our earlier concepts. The one unexpected feature is the temporary increase of discharge for the minute or so after simulated rainfall has ceased; yet even that should have been forecast.

Apparently the disturbance caused by the impact of large raindrops may be compared to the interference of a forest of pegs; or perhaps a number of garden-rakes aligned successively across the strip with handles down the slopes, would be a better illustration. In order to induce the required flow among such obstructions, the depth of storage or detention would have to be increased. Now, remove the rakes as suddenly as the sprinkling-system is turned off, and that excess volume would be released to pile up on the last element of stream-flow equivalent to rainfall-rate. In nature, this particular phenomenon is seldom if ever encountered, as the storms ease off from several inches per hour, to two, or one, or less than one inch, thus permitting the detention-volume to be reduced gradually, tending to prolong maximum discharge, rather than to establish a new maximum.

The paper has much of practical value among industrial and airport and metropolitan developments; it was well presented.

THERMAL TRANSFER OF MOISTURE IN SOILS

W. O. Smith

In a pioneer paper, BOUYOUCOS [see 1,2 of "References" at end of paper] published experimental work in which he attempted to show that soil-moisture moved from a warm and moist soil to a cold and dry soil. The movement, although he is not specific, was in the direction of the temperature-gradient.

Ordinarily, moisture moves in a soil because of body-forces, such as gravity, capillary forces, or vapor-transfer. Some, but not all, of these are altered by thermal influences. Gravity is not; capillary and vapor-movement are. Simple experiment shows that a bubble of water placed in a cylindrical capillary will move through the tube when a thermal gradient is applied in the direction of the tube. Consideration of the Kelvin equation [10] shows that capillary curvatures change with vapor-pressure. Vapor-pressures depend upon temperature; hence, vapor-movement is also expected. It is important to learn what thermal influences are able to move soil-moisture, and the magnitude of the transfer induced by each. The question is most directly answered by experimental investigation.

Bouyoucos [1,2] used the simple apparatus shown in Figure 1-A. It consisted of a container divided by a partition to form two chambers, one to be filled with hot water and one to be filled with cold water. The soil was placed in brass tubes eight inches long and 1-1/2 inches in diameter, with moist soil in one-half and dry soil in the other. These, after sealing, were fastened in the partition so that the moist half of the soil-tube was in warm water and the dry half in cold water. The exact temperatures were recorded by thermometers placed in the liquid in each chamber. The assembly just described was used to investigate transfer in the horizontal direction. A slight modification [1,2] was made to study transfer in the vertical direction.

Two ranges of temperatures were used: First, 0°C for the cold chamber and 40°C for the warm chamber; second, 0°C for the cold side and 20°C for the warm side. The soils investigated were moistened and then sieved; thus, they were fragmented and not in a natural state. After standing eight hours in the chambers, with temperatures in each maintained constant at the selected values, the soil-tubes were removed, and the moisture in each half determined by oven drying at 105°C. For this purpose, all the soil in the warm length of the tube, up to the plane of the partition, was counted as warm soil, and all the soil in the cold length, up to the plane of the

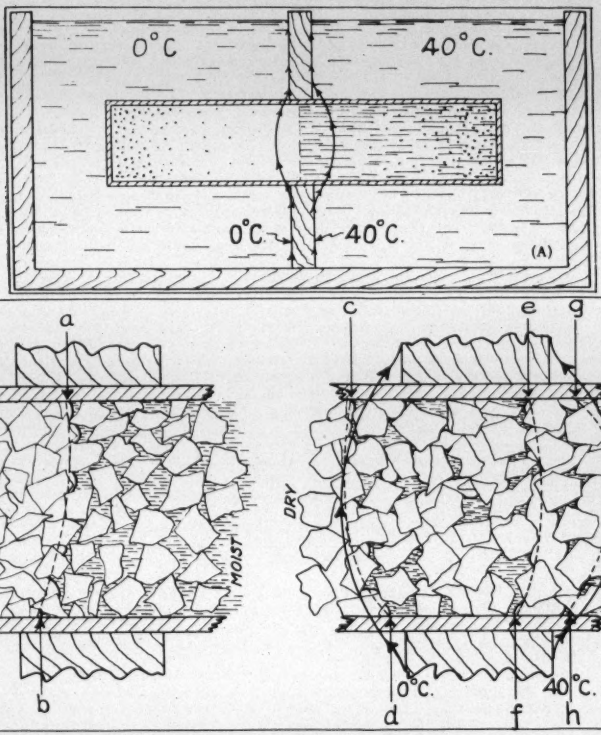

Fig. 1--Apparatus used by Bouyoucos to determine thermal transfer
(A) Sketch of apparatus; (B) water-fronts (ab) in soil-tube before application of gradient; (C) water-fronts after gradient has been applied [(cd) meniscus at cold front, (gh) meniscus at warm front, (ef) marks a probable separation of the region of transfer into a very wet and a very dry layer, wet toward cold front, dry toward warm]

partition and including that placed within the hole of the partition, was removed as cold soil.

Bouyoucos [1,2] found that thermal transfer did occur, and, further, that it was not influenced by gravity. As long as identical percentages of moisture were used, the results were the same whether the tube was placed horizontally or vertically. He further found that, with the lower moisture-contents, the transfer increased as the moisture-content of the soil until a particular value, which he called the "thermal critical moisture-content", was reached, where the transfer of moisture from the warm to the cold part of the tube was a maximum. At moisture-contents greater than this, the thermal transfer decreased as the moisture-content increased. The transfer at very low moisture-contents and again at very high moisture-contents was negligible. The results are shown graphically in Figure 2. Several textures, ranging from sandy loam to clay were investigated. The upper diagram shows results when the temperatures on the warm and cold parts were 0°C and 20°C, respectively; the lower diagram shows results for temperatures of 0°C and 40°C. The water-transfer, at most, is 1.3 per cent by weight for the 20°C-interval and 3.7 per cent for the 40°C-interval.

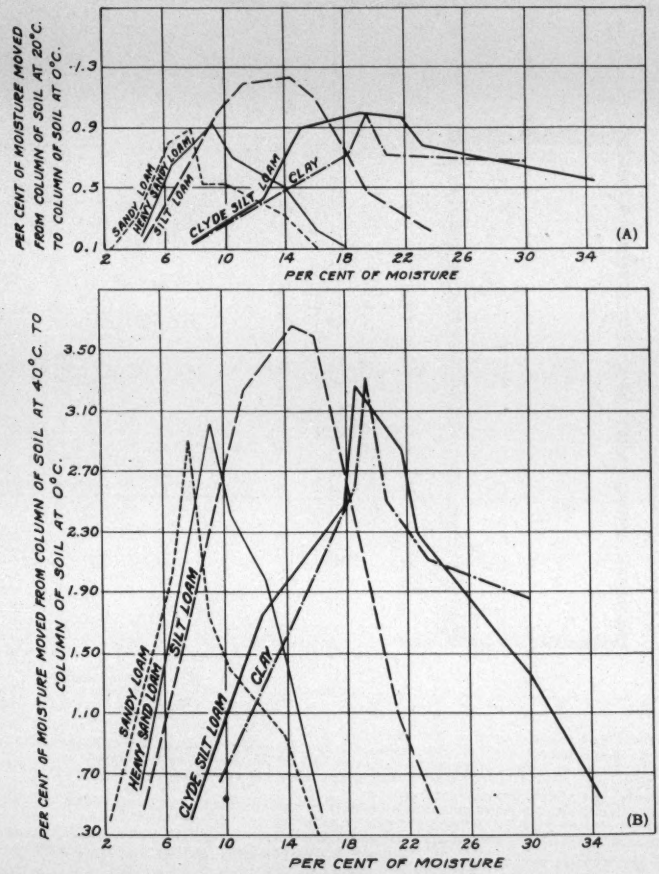

Fig. 2--Graphical representation of Bouyoucos' data
(A) Moisture transfer for temperature-range 0°C to 20°C; (B) transfer for 0°C - 40°C

The values, just given, represent a small transfer of moisture. The procedure of Bouyoucos [1,3], however, is subject to question. In Figure 1-A, it will be observed that each tube projects four inches or so into each of the constant-temperature baths. Therefore, most of the soil in a given section assumes the temperature of the bath in which it is immersed. Close to and under the partition, however, there is a large temperature-gradient across the soil, and it is in this region that water is transferred. There is little transfer outside this region; each half of the soil, external to it, has its own constant temperature (see Figs. 1-B and 1-C). Bouyoucos' results are referred to the soil of the whole four-inch section, rather than to that close to the partition. The magnitude of the effect is, therefore, considerably masked. Actually the writer [6] has observed

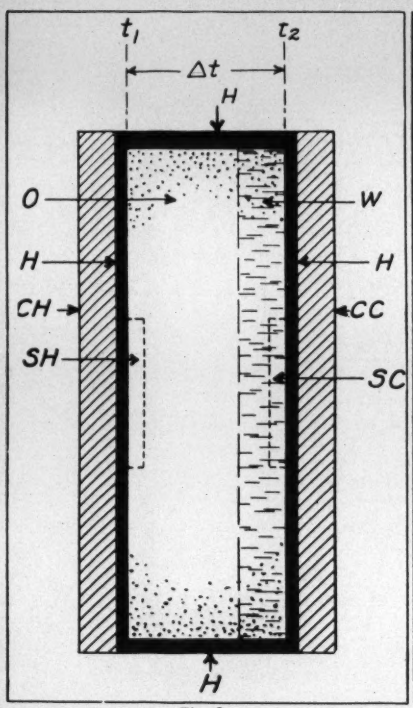

Fig. 3

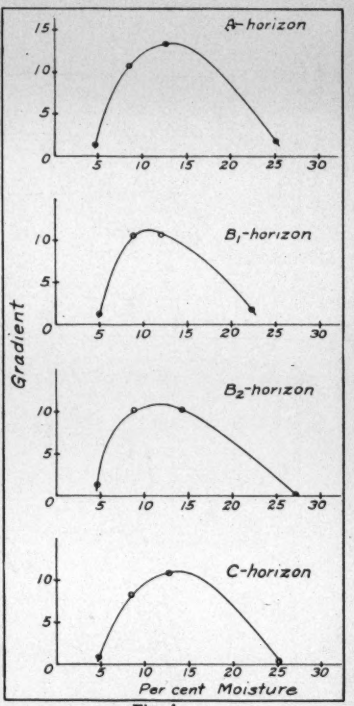

Fig. 4

Fig. 3--Apparatus used to determine thermal transfer
Gradient is applied across whole soil-mass; CH is the copper hot-plate, CC is copper cold-plate, H is hard-rubber soil-container,(O is dry soil, W is wet), SH is sub-sample on dry side, SC is sub-sample on cold side, t_1 and t_2 are temperatures of hot and cold faces, respectively, and Δt corresponding difference

Fig. 4--Moisture-gradients represented as a function of water-contents for Barnes loam (These gradients represent weights of water transferred per unit-weight of soil)

a much larger transfer to occur for gradients that are considerably smaller than those used by Bouyoucos.

The writer's investigations [6] were on the thermal conductivities of moist soils, and moisture-transfer was found to enter as a complication. Fragmented soils were used. These were placed in hard-rubber containers three-fourths of an inch or so thick with square faces eight inches on a side, as shown in Figure 3. The temperature-gradients were applied across the short dimension. Heat was released at a hot face CH, transmitted across the soil, and picked up by a cold reservoir CC. A known gradient was applied, by this procedure, across the whole soil. Details of the apparatus are given elsewhere [5].

To determine soil-moistures, samples were taken at SH of Figure 2 just next to the hot face, and at SC of Figure 2 next to the cold face. The water-contents in these small sub-samples were determined by oven drying at 105°C for 24 hours, and are given in gm of water per gm of dry soil.

Table 1--Moisture-transfer in Barnes loam

Laboratory number	Horizon	Initial moisture, gm water per gm dry soil	Final moisture-distribution, gm water per gm dry soil		Temperature gradient,[a] °C/cm	Approximate moisture-point
			Warm side	Cool side		
(1)	(2)	(3)	(4)	(5)	(6)	(7)
C2929	A	0.0508	0.0432	0.0564	5.5	75 per
C2930	B_1	0.0496	0.0437	0.0556	5.0	cent rela-
C2931	B_2	0.0490	0.0432	0.0567	4.6	tive hu-
C2932	C	0.0492	0.0398	0.0474	4.3	midity
C2929	A	0.0893	0.0572	0.166	4.9	99 per
C2930	B_1	0.0886	0.0566	0.162	4.8	cent rela-
C2931	B_2	0.0890	0.0611	0.162	4.2	tive hu-
C2932	C	0.0851	0.0558	0.138	3.9	midity
C2929	A	0.130	0.0850	0.219	4.5	50 per
C2930	B_1	0.121	0.0813	0.187	4.0	cent mois-
C2931	B_2	0.144	0.105	0.208	3.6	ture-equiv-
C2932	C	0.127	0.0794	0.187	3.7	alent
C2929	A	0.266	0.261	0.280	2.7	100 per
C2930	B_1	0.222	0.218	0.237	2.6	cent mois-
C2931	B_2	0.271	0.266	0.269	2.3	ture-equiv-
C2932	C	0.252	0.244	0.249	1.8	alent

[a] Thickness of sample = d = 1.91 cm.

Each included the soil in a space 1-1/2 inches square and 1/8 inch thick, or so, depending upon the thickness of the wet layer. A thickness less than 1/8 inch was used when this was smaller. In many cases, a soil, wetted homogeneously when initially placed in the container, was separated, by action of the gradient, into a very wet and a very dry layer. Photographs of some samples are shown in another publication [6].

Table 1 shows data for the Barnes loam. Initial moistures are given, also data on actual thermal transfers of moisture. It will be observed that at 50 per cent moisture-equivalent a transfer of 100 per cent is observed instead of about four per cent, as observed by Bouyoucos. This difference is caused by his experimental procedure that referred the results to a much larger mass of soil than that in which transfer actually occurred.

In the author's experiments, the differences between the water-contents on the hot and cold sides, after transfer, were called the moisture-gradients. In Figure 4, these are represented as a function of the water-content (expressed as a percentage of the dry weight of the soil), for the Barnes loam. The four points on each curve, beginning at the one nearest the origin, represent approximately, in order, the moisture-gradients observed when the water-content is that in equilibrium with relative humidity of 75 per cent, then relative humidity of 99 per cent, then a water-content of 50 per cent moisture-equivalent, and finally 100 per cent moisture-equivalent. It will be observed that little transfer occurs at relative humidity of 75 per cent, but at a point just under 99 per cent large water-transfer begins to occur; at about 50 per cent moisture-equivalent it is a maximum; at 100 per cent it is again negligible. These curves are similar to those observed by Bouyoucos (see Fig. 2), except the water-transfers are much larger.

The published investigations of Bouyoucos [1,2] and the writer [6] have been, to date, entirely on fragmented soils. The writer has recently shown [7] the physical condition of the soil to influence the transfer of heat greatly. Thus, the transfer of heat in a natural soil of blocky structure is much greater than in the same soil when fragmented by crushing and passing through a two-mm sieve, both being in the air-dry condition.

Comparative studies were made of the Miami silt-loam, the Miami silty clay-loam, and the Chester loam, under both moist and air-dry conditions, when in the natural state and again when fragmented. Thermal conductivities and moisture-transfers, under the applied temperature-gradients, were measured. An account of the moisture-transfer investigations will be given here,

Table 2--Moisture-transfer in moist monoliths

Soil	Horizon	Laboratory number	Initial moisture, gm water per gm dry soil	Final moisture-distribution, gm water per gm dry soil		Temperature gradient, °C/cm	Moisture-gradient[b], gm water per gm dry soil	Volume weight, gm/cc
				Warm side	Cool side			
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Miami silty clay-loam	A_1	C6615	0.159	0.106	0.205	2.1	0.099	1.29
	A_3	C6616	0.104	0.104	0.111	1.2	0.007	2.02
	B_2	C6617	0.154	0.143	0.154	1.2	0.011	2.04
	B_3	C6618	0.124	0.121	0.146	1.3	0.025	2.04
	C	C6619	0.132	0.107	0.136	1.4	0.029	1.99
	V_B[a]	C6620	0.183	0.177	0.189	1.2	0.012	1.99
Miami silt loam	A_1	C6621	0.211	0.124	0.262	2.1	0.138	1.34
	A_2	C6622	0.110	0.097	0.127	1.2	0.030	1.56
	A_3	C6623	0.126	0.118	0.142	1.2	0.024	1.82
	B_2	C6624	0.157	0.143	0.160	1.3	0.017	1.95
	B_3	C6625	0.175	0.174	0.199	1.3	0.025	1.87
	C	C6626	0.109	0.107	0.122	1.2	0.015	2.05
	V_B[a]	C6627	0.113	0.123	0.152	2.6	0.029	1.89
Chester loam	A_2	C6628	0.323	0.305	0.330	1.4	0.025	1.63
	B_2	C6629	0.243	0.239	0.252	1.2	0.013	1.91
	C	C6630	0.216	0.183	0.223	1.6	0.040	1.80

[a] V_B denotes sample taken vertically through B-horizon. [b] Thickness of sample = d = 2.54 cm.

since it shows the physical condition of the soil to influence greatly the amount of moisture transferred under a small temperature-gradient.

The same monolith furnished soil to investigate the influences of both the natural and fragmented conditions. Measurements were made on the monoliths in the moist state, then again when air-dried. The monoliths were then crushed and sieved (2-mm) and measurements made, first, in the air-dried state, and second, when wetted to moisture-contents equivalent to those in the original monoliths. Each fragmented sample contained the weight of water per unit-weight of soil which existed in the original monolith.

The method of measurement was the same as described elsewhere [5,6]. Monolith samples were allowed to come to thermal equilibrium which generally required 24 hours or more. The same procedure was used for the fragmented samples. After the thermal conductivities and temperature-gradients for the sample were determined, the supporting hard-rubber face-plates were removed and sub-samples, about 1/8 inch thick and one inch square, taken from three different locations on each face. These were taken just outside the area covered by the plate and close to the inner edge of the guard-ring. The holes left were patched and smoothed over with wet soil from the original monolith; the block was then left to dry for further measurement. The sub-samples were oven-dried 24 hours at 105°C.

Table 2 shows the results for wet monoliths. The initial moisture of the block was determined by the difference in its weights before and after drying. The blocks were allowed to become air-dry, and again measured. The results are shown in Table 3. The air-dried blocks were fragmented by crushing and sieving through a two-mm sieve, and the resulting samples measured. The data are shown in Table 5. The air-dried fragmented samples were moistened and measured. The data are shown in Table 4. Table 6 shows some moisture-characteristics of the soils.

Moisture-gradients, that is, the difference between the moisture-contents on the warm and cool sides, are included in the Tables. The thickness of monolith samples was one inch, while that of the fragmented sample was 3/4 inch. If true moisture-gradients are computed the difference between them, for natural and fragmented conditions, will be increased; the natural samples will show a relatively smaller transfer. Initial moisture-contents, just prior to applying the temperature-gradient, as well as temperature-gradients, are shown in all Tables.

Table 3--Moisture-transfer in air-dried monoliths

Laboratory number	Initial moisture, gm water per gm dry soil	Final moisture-distribution, gm water per gm dry soil		Temperature-gradient, °C/cm	Moisture-gradient[a], gm water per gm dry soil	Volume-weight, gm/cc
		Warm side	Cool side			
(1)	(2)	(3)	(4)	(5)	(6)	(7)
C6615	0.0221	0.0171	0.0302	6.2	0.0131	1.16
C6616	0.0127	0.0123	0.0134	2.8	0.0011	1.84
C6617	0.0261	0.0233	0.0268	2.6	0.0035	1.82
C6618	0.0252	0.0223	0.0263	2.5	0.0040	1.83
C6619	0.0221	0.0204	0.0225	2.4	0.0021	1.80
C6620	0.0221	0.0213	0.0224	2.9	0.0011	1.73
C6621	0.0234	0.0204	0.0247	4.9	0.0003	1.12
C6622	0.0160	0.0151	0.0156	3.4	0.0005	1.47
C6623	0.0193	0.0188	0.0198	2.7	0.0010	1.63
C6624	0.0376	0.0345	0.0376	3.6	0.0031	1.73
C6625	0.0381	0.0340	0.0390	3.0	0.0050	1.64
C6626	0.0126	0.0119	0.0126	2.3	0.0007	1.85
C6627	0.0318	0.0300	0.0343	3.3	0.0043	1.74
C6628	0.0125	0.0112	0.0125	4.4	0.0013	1.24
C6629	0.0113	0.0108	0.0112	3.2	0.0004	1.55
C6630	0.0069	0.0037	0.0077	4.1	0.0040	1.49

[a]Thickness of sample = d = 2.54 cm.

Table 4--Moisture-transfer in moist fragmented soils

Laboratory number	Initial moisture, gm water per gm dry soil	Final moisture-distribution, gm water per gm dry soil		Temperature-gradient, °C/cm	Moisture-gradient[a], gm water per gm dry soil	Volume-weight, gm/cc
		Warm side	Cool side			
(1)	(2)	(3)	(4)	(5)	(6)	(7)
C6615	0.147	0.0536	0.224	3.4	0.170	1.11
C6616	0.100	0.0526	0.139	3.1	0.083	1.25
C6617	0.139	0.111	0.193	3.2	0.082	1.07
C6618	0.115	0.0738	0.190	3.6	0.016	1.17
C6619	0.113	0.0797	0.170	3.1	0.090	1.19
C6620	0.142	0.0914	0.203	3.4	0.112	1.11
C6621	0.210	0.146	0.265	2.8	0.119	1.03
C6622	0.106	0.0506	0.166	3.6	0.115	1.20
C6623	0.106	0.0503	0.163	2.9	0.113	1.18
C6624	0.124	0.0765	0.187	3.9	0.110	1.18
C6625	0.146	0.0874	0.217	4.0	0.130	1.12
C6626	0.103	0.0754	0.136	2.7	0.061	1.23
C6627	0.0865	0.0684	0.127	4.1	0.059	1.32
C6628	0.265	0.253	0.256	2.3	0.003	1.26
C6629	0.248	0.254	0.254	2.3	0.000	1.24
C6630	0.241	0.239	0.241	2.1	0.002	1.24

[a]Thickness of sample = d = 1.91 cm.

Table 5--Moisture-transfer in air-dried fragmented soils

Laboratory number	Initial moisture, gm water per gm dry soil	Final moisture-distribution, gm water per gm dry soil		Temperature-gradient, °C/cm	Moisture-gradient[a], gm water per gm dry soil	Volume-weight, gm/cc
		Warm side	Cool side			
(1)	(2)	(3)	(4)	(5)	(6)	(7)
C6615	0.0204	0.0179	0.0203	6.3	0.0024	1.00
C6616	0.0145	0.0124	0.0147	4.4	0.0023	1.45
C6617	0.0236	0.0202	0.0258	5.7	0.0056	1.12
C6618	0.0245	0.0227	0.0268	5.0	0.0041	1.37
C6619	0.0213	0.0194	0.0245	4.5	0.0051	1.37
C6620	0.0257	0.0228	0.0277	5.4	0.0049	1.22
C6621	0.0265	0.0224	0.0273	5.7	0.0049	1.11
C6622	0.0150	0.0145	0.0162	4.9	0.0017	1.24
C6623	0.0190	0.0169	0.0196	4.5	0.0027	1.30
C6624	0.0349	0.0333	0.0411	5.2	0.0078	1.24
C6625	0.0332	0.0318	0.0358	4.8	0.0040	1.19
C6626	0.0135	0.0134	0.0149	4.2	0.0015	1.53
C6627	0.0347	0.0299	0.0353	4.9	0.0054	1.23
C6628	0.0114	0.0105	0.0122	5.7	0.0017	1.09
C6629	0.0096	0.0091	0.0103	4.9	0.0012	1.25
C6630	0.0054	0.0049	0.0055	4.7	0.0007	1.23

[a]Thickness of sample = d = 1.91 cm.

Table 6--Summary of reference-moistures

Laboratory number	Moisture required for 50 per cent relative humidity, gm water per gm soil	Moisture required for 75 per cent relative humidity, gm water per gm soil	Moisture required for 99 per cent relative humidity, gm water per gm soil	Moisture-equivalent, per cent
(1)	(2)	(3)	(4)	(5)
C6615	0.0209	0.0253	0.0470	26
C6616	0.0157	0.0209	0.0438	19
C6617	0.0238	0.0316	0.0720	22
C6618	0.0260	0.0355	0.0795	24
C6619	0.0231	0.0316	0.0753	23
C6620	0.0246	0.0340	0.0737	23
C6621	0.0221	0.0279	0.0530	29
C6622	0.0154	0.0200	0.0406	24
C6623	0.0183	0.0225	0.0426	23
C6624	0.0339	0.0440	0.0821	25
C6625	0.0375	0.0517	0.105	27
C6626	0.0133	0.0176	0.0400	17
C6627	0.0351	0.0480	0.0934	25
C6628	0.0115	0.0158	0.0415	29
C6629	0.0134	0.0205	0.0715	30
C6630	0.0063	0.0090	0.0272	20

Figure 5 shows moisture-gradients represented as functions of the moisture-content, per unit-weight of soil, expressed as a percentage. The A-horizons of all soils are plotted in Figure 5-A. Similarly, data for the B- and C-horizons are shown in Figures 5-B and 5-C. Results for natural and fragmented conditions are shown in a single diagram. This procedure was used since but two moistures were obtained for each sample. These soils do not appear to differ sufficiently in their moisture-behavior to prevent use of a composite diagram to indicate the variation of moisture-gradients with moisture-content. The curves are, however, not complete and can be used only to judge, approximately, the behavior.

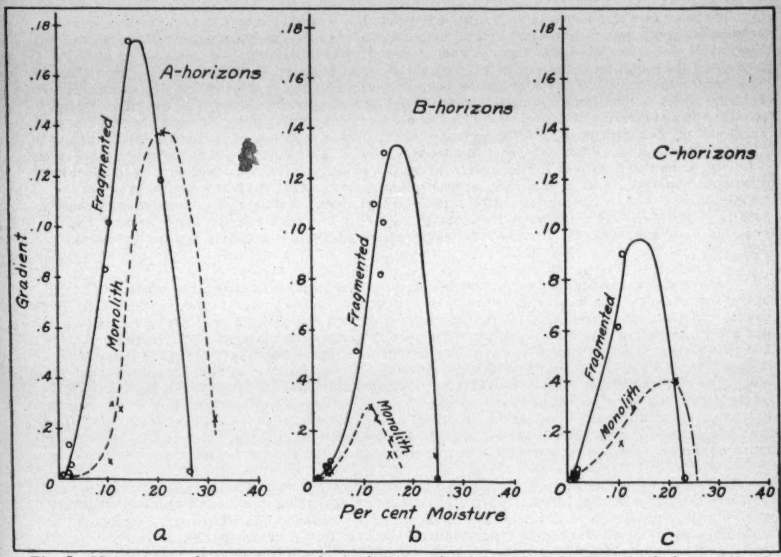

Fig. 5--Moisture-gradient represented as a function of water-content for Miami silt-loam, Miami silty clay-loam, and Chester loam: a = A-horizons of soils; b = B-horizons; c = C-horizons (These gradients represent weights of water transferred per unit-weight of soil)

It will be observed that when the water-content is about half moisture-equivalent, moisture-transfer is a maximum. At a point just above the moisture required for equilibrium with relative humidity of 75 per cent, as well as at moisture-equivalent, moisture-transfer is negligible. This is in accordance with earlier observations of Bouyoucos [1,2] and the writer [6]. It appears to be independent of the physical condition of the soil.

The physical condition of the soil affects the magnitude of the observed transfer, greatly. For the A-horizons of the soils shown in Figure 5-A, where the structure is granular, fragmentation has only a moderate effect in elevating moisture-transfer. When, however, the structure is blocky as in the B-horizons, shown in Figure 5-B, fragmentation has a pronounced effect, with moisture-transfer being increased up to seven-fold. In the C-horizons, shown in Figure 5-C, fragmentation doubles the moisture-transfer. The maxima of the curves for natural soils seems to be somewhat displaced with respect to those obtained for the fragmented condition. Additional data, however, are needed to establish this point.

The temperature-gradients are all small, but differ in value somewhat. The differences are not believed sufficient to affect appreciably the magnitude of the moisture-transfers observed. Further evidence on this point is obtainable from the data of Tables 2 and 3, on moist-monolith and moist-fragmented soils, respectively, having approximately the same moisture-contents and temperature-gradients. Monolith sample C6627 has a moisture-content of 0.113 gm of water per gm of dry soil, and a temperature-gradient of 2.6 C per cm. Fragmented samples C6623 and C6626 have, respectively, moisture-contents of 0.106 and 0.103, and temperature-gradients 2.9 and 2.7. The moisture-gradient of the monolith-sample is 0.029 while those of the fragmented samples are respectively 0.113 and 0.061. All temperature-gradients are about equal and all moisture-contents are about equal, but the moisture-gradients are quite different. The physical condition and not the temperature-gradient appears to control the effect especially when the temperature-gradients are small.

Transfer of water under temperature-gradients can be effected by either or both of two processes, first, vapor-movement and subsequent condensation, and second, capillary movement. Bouyoucos [1,2] concluded that vapor-transfer in soils was negligible. To this end, he initially separated the moist from the dry soil (fragmented) in an eight-inch tube, by an air-ring. This device breaks the capillary contacts and permits only vapor-transfer through the air space. The air-ring was 1/4 inch thick and maintained by wire-gauze barriers inserted in the tube. He applied the temperature-gradients, which he had used earlier, for a period of eight hours. For the ranges of temperature of 0° to 40°C he found transfer to be 0.25 per cent, and for the ranges of 0° to 20°C the value was 0.035 per cent. It appears, from this experiment, that the larger part of the water os moved by capillary forces, while a small part only travels as vapor when a temperature-gradient is applied. This experiment is open to the objection that the temperature-gradient is chiefly across the air-space, with little of the soil included; his values are, therefore, extremely small. CURTIS [3] has questioned the procedure used by Bouyoucos in this experiment. It appears to be sound, however, provided the temperature-gradient is properly applied across the soil.

The writer performed an experiment, along the same lines, with apparatus similar to that shown in Figure 3. The hard-rubber face-plates covering the soil were replaced with coarse-wire gauze, and a soil slab one inch thick placed between the hot and cold plates. The gauze-barriers had a lead edging, so that the frame, containing the coil, could be clamped tightly between the hot and cold plates. Free drainage was provided along the gauze at the cold face, into a glass tube (5-mm bore) placed at the bottom of the soil-frame. The air gap, at the cold face, was about one mm. The soil was wet to moisture-equivalent. Temperatures of 65°C on the hot face, and 25°C on the cold face, were maintained for four days. No water drained off the cold face. It appeared to hold on its surface only a moderate amount of condensed moisture. A difference of only 0.5 per cent in moisture-content was observed between the soil-sample at the hot face and the soil-sample at the cold face. Therefore, very little water moved out of the soil as vapor.

The most perplexing observation, if we examine the data, is that the thermal transfer of moisture begins to be appreciable at a moisture-content just above that required for equilibrium with relative humidity of 75 per cent, and then practically ceases at about moisture-equivalent. If the behavior were wholly due to vapor-transfer, be it diffusion or convection, it would appear that it ought to proceed continuously. It should commence as soon as any water was present in the soil, and continue until transfer to the colder regions had taken place. The curvatures of the capillary surfaces will be completely adjusted, according to the KELVIN equation [10], to the vapor-pressures prevailing under the temperature-gradient when equilibrium has taken place. If the temperature-gradient is very small, only a moderate alteration of the moisture-distribution will occur. But if it is large, a great difference in moisture should exist between the cold and the warm parts of the soil. The moisture-contents at which the effect begins are on the steep part of the vapor-pressure - moisture isotherm. The whole effect appears to be confined to the region of funicular water. It does not appear, therefore, that the observed transfer is caused wholly by vapor-movement; hence the action of capillary forces must be considered.

If a globule of water is placed in a cylindrical capillary tube and a temperature-gradient applied in the direction of the capillary, as in Figure 6, the meniscii at each end of the globule are at different temperatures. Now the surface-tension of a liquid depends upon temperature and generally decreases with rise of temperature. A tractive force, tending to pull the globule to the cool ends of the tube, therefore, exists. The amount of such tractive force T is, assuming complete wetting, $2\pi r\sigma - 2\pi r\sigma(1 - \alpha\Delta t)$, or $T = 2\pi r\sigma\alpha\Delta t$ where r is the radius of the capillary, σ is the surface-tension at the temperature t_c prevailing on the cool side of the globule, α is the temperature-coefficient of surface-tension, and Δt is the temperature-difference across the globule. The force T becomes zero only when $\alpha = 0$, or when $\Delta t = 0$. The expansion of the glass capillary along its radius is negligible. Consideration of this correction for glass, with a linear expansion-coefficient β, results in a tractive force, to a first approximation, $T = 2\pi r\sigma(\alpha - \beta)\Delta t$. For water at 25°C, $\alpha = 0.16 \times 10^{-2}$; for glass $\beta = 0.10 \times 10^{-4}$. Hence the thermal expansion of the glass need not be considered.

In soils a multiple conical capillary exists [8] rather than a simple cylindrical one, and the effect is complicated. To illustrate the behavior of such a capillary under a temperature-gradient, consider a globule of liquid enclosed within the opening formed by three spherical grains. The meniscus-grain contour will be somewhat irregular. At the contact points of the spheres it will rise, but be lower between them, as shown in Figure 7. For a first approximation, effects of distortion such as these need not be considered [8,9], and the meniscus-grain perimeter may be considered to lie in a plane, the plane of the meniscus, passing through the lowest point of the contour.

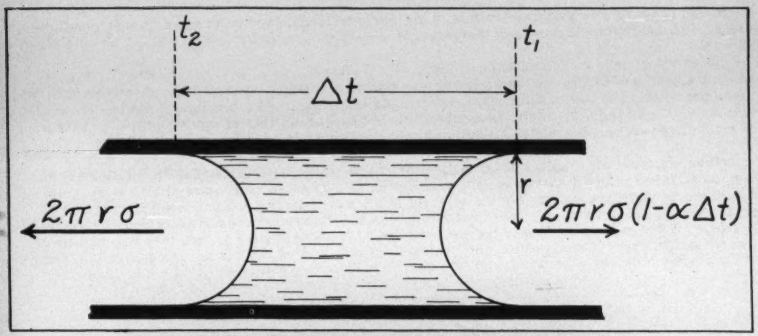

Fig. 6--Capillary forces acting on globule of liquid in a cylindrical capillary when subjected to a thermal gradient

The globule, before application of the gradient, will be symmetrical about the plane formed by the centers of the three grains; after application it is not. The gradient is supposed to be along the axis of the cell which is normal to the plane of the meniscus. Consider the upper surface of the globule lying within the triangle ABC, in the plane of the meniscus, whose vertices are just over the grain-centers; and similarly the lower surface of the globule lying within a corresponding triangle. To a first approximation, the tractive force T, along the axis of the cell (perpendicular to the plane of centers), tending to advance the bubble to the cool end is $T = [\pi r \sigma \cos^2 \theta_1 - \pi r \sigma (1 - \alpha\Delta t) \cos^2 \theta_2]$; where θ_1 is the angle on the cool end, between the plane of centers and the radius-vector to the plane of the meniscus [8], and θ_2 a similar angle on the

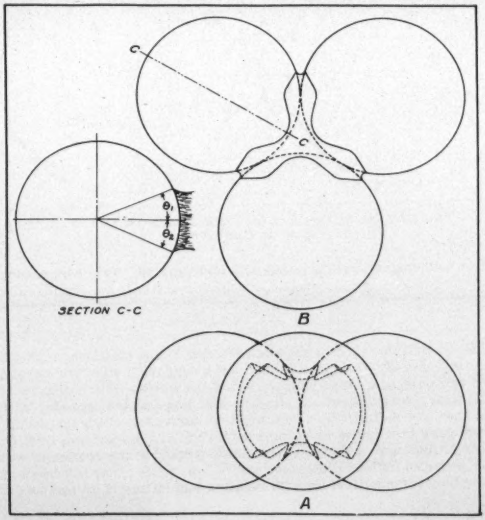

Fig. 7--Globule of liquid included by a cell formed from three spherical grains: A = complete globule; B = top of globule

warm end (Fig. 7), r is the grain-radius, σ the surface-tension and α its temperature-coefficient, and Δt, finally, is the difference of temperature across the globule.

When the globule has come to equilibrium $T = 0$ and $\cos^2 \theta_1 = [(1 - \alpha\Delta t) \cos^2 \theta_2]$. With $\Delta t = 10°C$, $\alpha = 0.0016$, the angles θ_1 and θ_2 are practically equal. The globule, therefore, will advance but little. The parts of the meniscus outside the triangle ABC are small, but can be treated similarly. Capillarity, by itself, therefore, does not appear capable of producing thermal transfer of moisture in soils subjected to ordinary temperature-gradients.

There is, however, another mechanism that is effective, particularly before equilibrium has been established. Only a short physical description will be given here. Just after a temperature difference is applied, capillary bodies adjacent to the warm plate are not in equilibrium, and begin to evaporate. The excess vapor condenses, to some degree, on the capillary bodies immediately ahead. If two of them are close together, as are A and B in Figure 8, then they will be brought into contact by vapor-condensation, and coalesce. The resulting body is not in equilibrium, and will move, by ordinary capillarity, into the cell immediately ahead on the cool side. Rings of

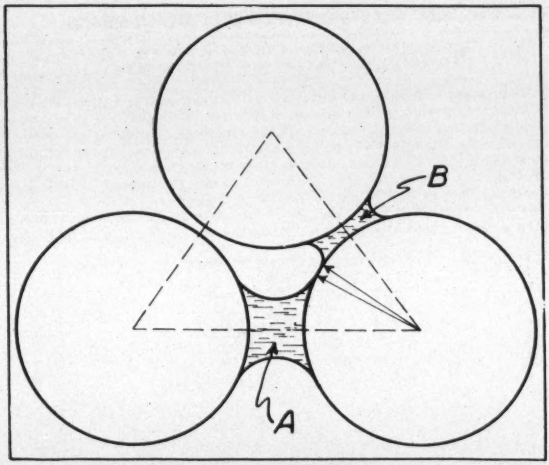

Fig. 8--Two globules of liquid in tetrahedral cell (shown in section) about to coalesce

liquid, only, are left around contact-points in the cell just vacated. Vapor-condensation has served as a trigger to start the process. It should continue until all the liquid, except that left as pendular water in the form of small rings around contact-points, has moved to the cool side of the sample.

The process evidently will not start if the bodies A and B are too far apart. For example, simple pendular rings will merely grow in size and again evaporate when the advancing heat-front reaches them. There will only be a slight adjustment of the water-distribution, namely, that required for equilibrium under the gradient. It appears that large water-transfer will first occur when the capillary masses are sufficiently close together for vapor-condensation to effect a coalescence and permit ordinary capillarity to become effective. This condition first occurs when a transfer from pendular to funicular water can take place without much change in water-content, that is, when pendular water is high and funicular water low. This point is somewhere between the water-contents required for equilibrium with relative humidities of 75 and 99 per cent, respectively.

If the pore-space is saturated, or nearly so, the soil-water is almost all in one mass and no transfer can occur. This is the condition found in heavy soils at moisture-equivalent. If, on the other hand, single threads of water extend from one side of the sample to the other, little transfer will occur. This is probably the case when the funicular water-content is large. This condition could occur in clays, in which case water-transfer would stop before moisture-equivalent was reached (the curves do not show data on this question). It also may occur in the finer sands near moisture-equivalent; the larger capillaries are unfilled, while the smaller are threaded with liquid. In coarse sands, however, the water held at moisture-equivalent is mostly pendular, and little or no transfer is expected at any water-content below this other than that arising from vapor-movement. If a sand has sufficient fine pores so that it may support funicular water below moisture-equivalent, transfer of the funicular water will occur. A small amount of fine material, such as silt, is sufficient to occasion some transfer. The transfer would ordinarily be small in sands since a small transfer is sufficient to remove the funicular water present. Thus no transfer is expected at moisture-equivalent in either the finer sands or clays, and therefore not for intermediate textures. Transfer under a temperature-gradient appears to be confined to funicular water.

Somewhere between the water-contents required by points roughly around relative humidity of 99 per cent and moisture-equivalent, respectively, transfer should be a maximum. It probably occurs when the water-content is moderately large and distributed uniformly in pendular and funicular masses, close together but just short of coalescence.

The reason that fragmented samples show much larger water-transfers than the same samples in their natural state now becomes apparent. The additional capillary space provided by small fragments becomes effective as a new capillary system, able to carry on the process and provide additional storage-space in the cool part of the soil. In A-horizons of medium or fine granular structure [NIKIFOROFF'S notation, 4], fragmentation by a two-mm sieve will increase the secondary pore-space but not to any great extent and the transfer will be only slightly larger. When B-horizons, of blocky structure, are fragmented, the secondary pore-space is greatly increased, and the water-transfer in the fragmented sample will be vastly greater for the same temperature-gradient. Similar remarks are applicable to C-horizons.

Conclusions--Moisture is transferred from a warm and moist soil to a cold and dry one only by the slow process of vapor-diffusion and possibly convection, except in the region of contact where a temperature-gradient exists. When a temperature-gradient is applied, a large transfer occurs for a limited range of moisture-conditions and is confined entirely to the region in which the temperature-gradient is applied. The mechanism appears to be capillary movement induced by vapor-condensation. Thermal transfer of moisture, even under small gradients, begins at a water-content roughly just below that required for equilibrium with relative humidity of 99 per cent and ceases approximately at moisture-equivalent. Thus, it occurs chiefly with funicular water. It reaches a maximum at about half the latter water-content, the "thermal critical moisture-content" of Bouyoucos. It is greatly influenced by the physical condition of the soil; for example, it is small in clays in a natural state, but large when in a fragmented condition. The conclusions reached are based on limited data. More investigation is required before a satisfactory account of the behavior is obtained.

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DISCUSSION

L. D. BAVER (North Carolina State College, Raleigh, North Carolina)--The author is to be commended for the clarity of presentation of this paper. His research approach has been well planned and executed. His generalizations on the limited amount of data are conservative. The logic of his reasoning appears sound and in line with recent concepts of soil-moisture movement.

The constructive criticism of the experiments of Bouyoucos is just and fair. The low transfer-values that Bouyoucos found undoubtedly can be attributed to the fact that the major movement took place in the narrow zone (across which there was a thermal gradient) between the cold and warm ends of the tube. The author points this out in a very plausible and constructive manner.

It is indeed significant that the author finds such a considerable transfer under a thermal gradient. These results will aid materially in helping to explain some of the differences of opinion that exist on the subject of the effect of moisture on thermal conductivity. The effect of the physical condition of the soil on the thermal transfer of water is clearly illustrated in Figure 5. This technique indicates the value of paying attention to the natural structure of soils in studying their physical properties.

The author confirms the work of Bouyoucos by showing that there is a given moisture-content at which thermal transfer is at a maximum. The fact that this maximum occurs at a moisture-content at about 50 per cent of the moisture-equivalent value is rather interesting. The fact that there was little transfer at relative humidity of 75 per cent opens the question as to the validity of many of our assumptions that there are such significant movements of water in the vapor-phase in soils. There happen to be several small pieces of evidence in recent years that seem to indicate we may have overstressed the significance of vapor-movement. The author's clever explanation that vapor-condensation may serve as a trigger to start the capillary processes is rather intriguing. It is my opinion that he probably is on the right track.

HEAVY MINERALS IN SEDIMENT-TRANSPORTATION STUDIES

Gordon Rittenhouse and E. M. Thorp

Introduction--In addition to quartz and feldspar, most river-sands contain minor amounts of magnetite, ilmenite, pyroxene, garnet, or other minerals of greater density than quartz and feldspar. The presence of these "heavy" minerals--particularly magnetite and ilmenite--may be indicated by dark-colored concentrates on top of bed-ripples, or by dark-colored layers within deposits of sand. Such minerals have been entirely neglected in studies of sediment-transportation in natural rivers and as parts of mixtures in flume-investigations. Because heavy minerals are subject to the same hydraulic conditions as the lighter minerals with which they are associated, they provide a means by which the influence of specific gravity (and shape) on the transportation of medium and fine sand may be investigated. A range in specific gravity from 5.2 to 3.1 will be commonly available.

In natural fluvial deposits, the size-distributions of heavy minerals are known to vary systematically with the size-distribution of the lighter minerals with which they are associated [see 7 of "References" at end of paper]. Much work remains, however, to determine the extent to which specific gravity, shape, and hydraulic factors govern these systematic variations, particularly to find why heavies of high specific gravity (>3.6) apparently behave differently than heavies of lower specific gravity.

Where sufficiently large suspended-load samples can be collected--as they can in the Rio Grande and other rivers of the southwest--the transportation of sediment in suspension can also be studied by the heavy-mineral method. The size-distribution of the heavy minerals and their concentration in different parts of vertical sections can be determined and compared with similar data for light minerals in the same samples, or for heavy and light minerals in the bed-deposits.

It is the purpose of this paper to outline the analytical technique that can be used in such investigations, and to present the results obtained from a study of three samples from a vertical section collected from the Rio Grande near Escondido, New Mexico. Because the samples in this vertical section were part of a series that were obtained for another purpose, hydraulic measurements of slope, velocity-distribution, etc., are not available. To a large extent, therefore, these data are only of illustrative value. Although they cannot be used to test equations that describe the vertical distributions of suspended load, they demonstrate that heavy minerals can be used

advantageously for this and related purposes where the requisite hydraulic data are available.

A fuller understanding of the hydraulics of bed-load and suspended-load transportation is necessary before many problems concerned with flood-control, irrigation, drainage, and soil-conservation may be solved. Heavy mineral investigations already have been used effectively [8] in solving one type of problem of vital importance to flood-control and soil-conservation, namely, in determining the relative importance of various sediment-sources in the Middle Rio Grande Valley, New Mexico, where channel-aggradation and other forms of injurious sedimentation have caused much flood-damage and drainage-impairment. The present paper is a by-product of this other study.

Analytical technique--Each sediment-sample collected, or a random split of about 100 grams from it, is weighed to the nearest 0.01 gm, placed in a nest of sieves in which the size of openings increases from fine to coarse approximately as the $\sqrt{2}$, and shaken for about 15 minutes. The sand retained on each sieve is removed and weighed. If there is much silt or clay in the sample, it should be removed by wet sieving before the sand is screened.

The sand retained on each sieve for which heavy-mineral information is to be obtained is weighed to the nearest 0.001 gm, and placed in acetylene tetrabromide (specific gravity 2.93) or bromoform (specific gravity 2.86) contained in filtering funnels equipped with rubber tubing and pinch-cocks [6]. The suspension is stirred at intervals and the heavy minerals that sink and the light minerals that float are removed to separate filter-papers, washed with ethyl alcohol, dried, and weighed to the nearest 0.5 mgm. Magnetite can be removed from the heavy-mineral fraction by a small horseshoe magnet. The magnetite and the minerals other than magnetite are weighed separately. An alternative method would be to separate the heavy and light minerals from an unsieved sample and then size the heavies by sieving. Two- or three-inch diameter sieves would be required because the amount of heavies would be small.

The non-magnetic fractions, or a random part of them, are mounted in Canada balsam or piperine on glass slides, and the relative frequencies of the various kinds of heavy minerals are determined by microscopic identification of 300 or more grains. The number-percentages so obtained are changed to weight-percentages by correcting for specific gravity. In this number-to-weight change, it is assumed that the average volume of all kinds of minerals in each size-grade is the same. Specific gravities of the non-magnetic fractions obtained by calculation check closely with specific gravities determined by pycnometer [8]. The total weight of the non-magnetic fraction is multiplied by the weight-percentage of each mineral to give the weight of each mineral in the size-grade. This rather devious method of obtaining the weight of each heavy mineral is necessary because the various minerals, except magnetite, cannot be separated cleanly from one another and weighed separately.

The discharge per unit of time can be computed for each heavy mineral in the size-grade from the original sample weight, the weight of the split, the water-discharge, and the weight of the heavy mineral. If size-distributions of the heavies in the entire sample are wanted, the weight of the heavy is determined for each size-grade smaller than 0.5 mm in the sample, the total weight in the sample found by summation, and the weight in each size-grade divided by the total. The size-distributions by weight so obtained are comparable with those ordinarily obtained by sieving. They are not directly comparable with size-distributions by number that may be obtained by measuring intermediate or average diameters by micro-projection methods.

Size-distributions by number can be obtained, however, by separating the heavy minerals from an unsieved sample, mounting a random split of the heavies, and then measuring the intermediate or average diameter of enough grains of each type of heavy mineral to define the size-distribution curve. HATCH [5] and GRASSY [4] have shown that such size-distribution curves are related to size-distribution curves by weight. Because two samples may have the same size-distribution but may carry different absolute amounts of heavies, the weight of heavies in any particular size-grade cannot be obtained from the number-distributions.

Heavy-mineral investigations of the type outlined are time-consuming. Provided five or more samples are analyzed, about 24 to 30 hours will be required to determine the size-distributions by weight in each sample. For data on individual size-grades, from three to four hours per size-grade per sample will be required. These estimates do not include the time required to collect the samples. If ordinary laboratory facilities and a petrographic microscope are available, however, the costs other than labor are small.

Vertical section: Entire samples--The three samples making up the vertical that is used for

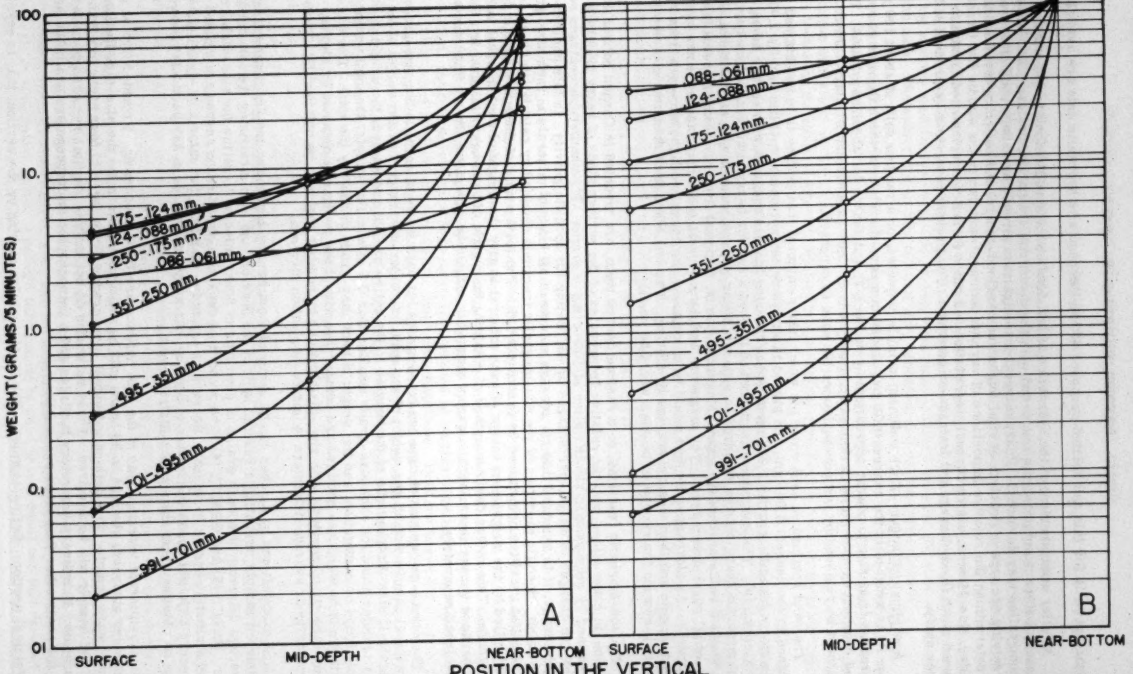

Fig. 1--Sediment-discharge for entire samples

illustration were taken from the Rio Grande near Escondido, New Mexico, on July 10, 1941, by Dr. S. C. HAPP, and are a part of a series collected on that and other days at Escondido and Albuquerque. The water-depth was about 7.7 feet, the average surface-velocity was about 4.5 feet per second and the river-discharge was about 4,000 cubic feet per second. The sampling apparatus consisted of a pipe, 2-1/2 inches in diameter and 12 inches in length, to the down-stream end of which was attached a coupling with a 100-mesh commercial wire screen soldered to the end. This apparatus was wired to a weight, whose torpedo-shape and fins kept the sampler approximately parallel to the flow-axis of the water. The pipe and attached weight were lowered by a rope to the desired depth and allowed to remain for a definite interval. The time of collection for the mid-depth and surface (upper one foot) samples was ten minutes and five minutes for the sample from about six inches above the bottom.

The surface, mid-depth, and near-bottom samples weighed 31.5, 73.5, and 443.4 gm, respectively, and the concentrations were about 12, 28, and 610 parts per million. Each sample was sieved, and the sediment-discharge per five minutes through the cross-sectional area of the sampler was computed for each size-grade. These data are plotted in Figure 1-A. Although three samples are not enough to define the vertical distributions very accurately, there is no doubt that the sediment-discharge for all sand-sizes increases toward the bottom, and that this increase is greatest for the coarsest sand. To show this relationship to better advantage, all size-grades of the near-bottom sample were assumed to have a sediment-discharge of 100 gm per five minutes. The discharges of the surface and mid-depth samples were then recomputed to this new base and the results plotted as Figure 1-B. The progressively greater differences in discharge between surface and bottom as the grain-size increases are clearly shown. This general relationship is that expected from theory [9] and is similar to that found in other natural rivers [1,2,3].

Vertical sections: Heavy minerals--The heavy minerals were separated from the size-grades 0.175 to 0.124 mm and 0.124 to 0.088 mm, and the weight of each kind of heavy in each size-grade was determined, using the methods just described. The discharge per five minutes of each kind of heavy mineral was computed and plotted in Figure 2-A. Like the entire samples, the discharge of various heavy minerals is greatest near the bottom. Next, the heavy-mineral discharge in the near-bottom samples was assumed to be equal to 100 gm per five minutes, and the surface and mid-depth discharges were recomputed to this new base. These data, together with similar data for the entire samples, are plotted in Figure 2-B. From this diagram, it is clear that the relative heavy-mineral discharge in the surface and mid-depth samples is considerably lower than that of the same size of sand in the entire sample; and that the discharge of magnetite (specific gravity 5.2) and ilmenite (specific gravity 4.7) is much lower than the discharge of pyroxene (specific gravity 3.4) and the hornblendes (specific gravity 3.2). Some such difference in relative discharge would be expected, because heavy minerals would settle at the same rate as lighter minerals of larger size.

To find whether density was the main factor involved, the relative surface-discharge of each size-grade was plotted against size (Fig. 3). The diameter of grains of density 2.65 that would settle at the same rate as each kind of heavy mineral (assuming spherical shape) was computed from RUBEY'S general-settling formula [10]. With this correction for density the pyroxene and hornblende discharges fit the entire sample curve very closely, but the magnetite and ilmenite discharges are too small. Data are insufficient to determine whether the low discharges of magnetite and ilmenite are due to sampling errors, or reflect the influence of factors other than density. In bed-deposits [7] ilmenite and magnetite show greater unexplained variations between samples than heavies of lower density.

Shape-measurements of Rio Grande sands from another locality indicate that ilmenite and the light minerals are very similar in shape [8]. In contrast, the pyroxenes are longer, and the hornblendes are flatter and stubbier than the light minerals. Thus, it is possible that the close relation of the corrected pyroxene and hornblende discharges to the entire sample discharges are due to both density and more irregular shape.

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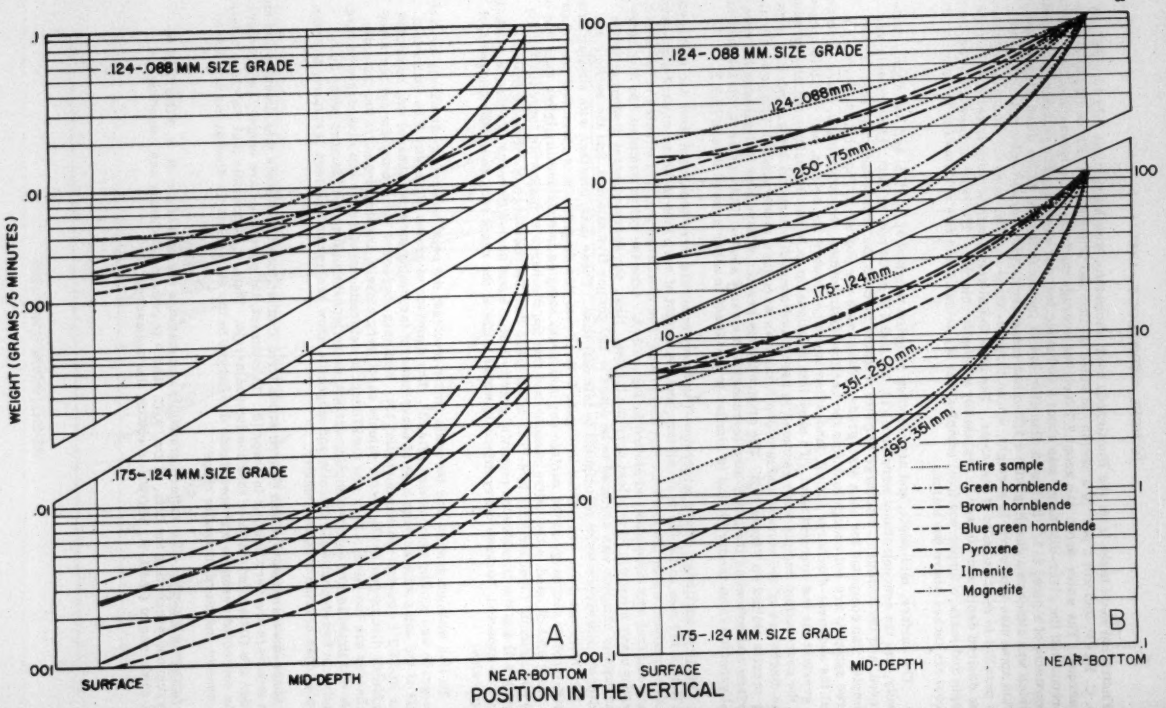

Fig. 2--Sediment-discharge for heavy-mineral samples

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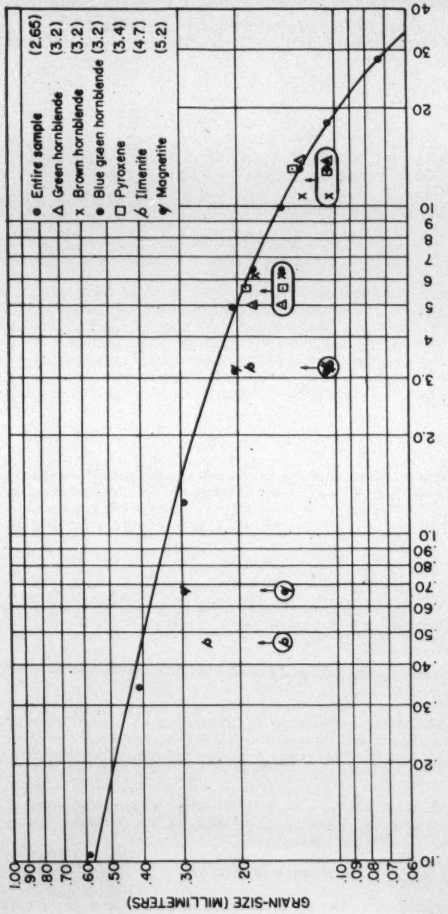

Fig. 3--Relative discharge and grain-size

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EXPERIMENTS ON EDDY-DIFFUSION AND SUSPENDED-MATERIAL TRANSPORTATION IN OPEN CHANNELS

A. A. Kalinske and C. L. Pien

In order to gain further insight into the fundamental mechanics of suspended-material transport by turbulent flow in open channels, a detailed program of studies was undertaken involving the direct measurement of eddy-diffusion coefficients and suspended-material concentrations. This paper outlines the important results of this study, and presents some typical data obtained. The measurements were made in two channels, one being 0.94 foot and the other 2.25 feet in width. For several slopes and water-depths in each channel, data were obtained on the distribution of mean velocity, diffusion-coefficients, and variation of sediment-concentration. The actual sediment-distributions were then compared with the theoretical distributions as calculated from the diffusion-coefficients. It appears that the diffusion-coefficients as measured directly by the method developed in these studies give an accurate indication of the mass-transfer characteristics of the turbulence.

(A) Theory of eddy-diffusion

The theory of continuous movements of masses of fluid in turbulent flow has been developed by G. I. TAYLOR [see 1, 2 of "References" at end of paper] in terms of a correlation-coefficient, R, between the velocity, v, of a fluid particle in a specified direction at any instant, and its velocity, v_t, an instant later. For example, for the velocity-component in the vertical direction this correlation-coefficient is

$$R = (\overline{v_t\, v}/\overline{v^2}) \tag{1}$$

where the bar indicates a time-average, and $\overline{v^2}$ is the root-mean-square value of the fluctuating vertical velocity, v. Taylor then showed the relation (2) to exist.

$$(d\,\overline{Y^2}/dt) = 2\,\overline{v^2}\int_0^t R\,dt \tag{2}$$

where Y is the distance traveled by any one particle in time t and $\overline{Y^2}$ is the mean square value of observed values of Y for a large number of particles. If Y is measured transverse to the turbulent flow, which is taken to be in the x-direction, then t can be replaced by (x/U), where U is the mean fluid velocity.

Analysis of equation (2) in the light of what is known about the general nature of turbulence leads us to several useful deductions. When t is very small then R is close to unity, which reduces equation (2), on substituting x/U for t, to equation (3).

$$(d\,\overline{Y^2}/dx) = (2\,\overline{v^2}\,x/U^2) \tag{3}$$

Thus indicating that $\overline{Y^2}$ varies as $\overline{x^2}$. As t (or x) becomes large the value of the correlation-

coefficient, R, becomes zero and then $\int_0^t$ Rdt becomes a constant, and equation (2) can be written as in equation (4).

$$(d\,\overline{Y^2}/dx) = (2\,\overline{v^2}\,x_0/U^2) \tag{4}$$

where $x_0 = \int_0^x R\,dx$ for values of x when R has become zero. Thus we note that the slope of the curve of $\overline{Y^2}$ against x becomes constant for large values of x. When this occurs the eddy-diffusion process is analogous to that of molecular diffusion for which a diffusion-coefficient is defined as

$$D = (U/2)\,(d\,\overline{Y^2}/dx) \tag{5}$$

By analogy we define an eddy-diffusion coefficient in the same manner; however, the value of $(d\,\overline{Y^2}/dx)$ used is the maximum value, as given by equation (4). Then by introducing D into equation (4) and integrating we have for large values of x

$$\overline{Y^2} = (2D/U)\,(x - x_0) \tag{6}$$

Thus if we can determine $\overline{Y^2}$ for various values of x it will be possible to determine the eddy-diffusion coefficient, D; and, if desired, the length factor x_0, which characterizes the scale of our turbulence, can be obtained. Also, it is possible to determine the intensity of the turbulence since

$$\overline{v^2} = DU/x_0 \tag{7}$$

Thus we have a means of obtaining a complete picture of the turbulence by direct measurement.

(B) Measuring the eddy-diffusion coefficient

The eddy-distribution coefficient can best be determined in a turbulent-water stream by injecting, at a particular point, matter that has the same density as the water so that it follows the eddy-movements exactly. One method tried was to inject through a small tube droplets of a liquid that had the same density as water but which did not mix with the water. A mixture of n-butyl phthalate and benzine was used, also, carbon tetrachloride and benzine. The liquid was colored dark and the position of the droplets downstream from the injector was photographed on motion-picture film. From the film it was possible to determine the spread of droplets transverse to the injector for various distances down-stream. By analyzing several hundred frames of the film, values of $\overline{Y^2}$ could be obtained for different values of x. By plotting $\overline{Y^2}$ against x the maximum value of $(d\,\overline{Y^2}/dx)$ could be obtained, and knowing the stream-velocity at the point of injection, the value of D could be calculated from equation (5). Because this method was quite laborious it was not used very much. Also, this method was not very feasible at high water-speeds, and, of course, could not be used with dirty water.

Diffusion-experiments in turbulent water indicated that the distribution of concentration of injected material transverse to the line of flow follows the normal error law. Thus the concentration C of any matter injected at a point x = 0 is given by

$$C = (M/\sqrt{2\pi\,\overline{Y^2}})\,e^{-Y^2/2\,\overline{Y^2}} \tag{8}$$

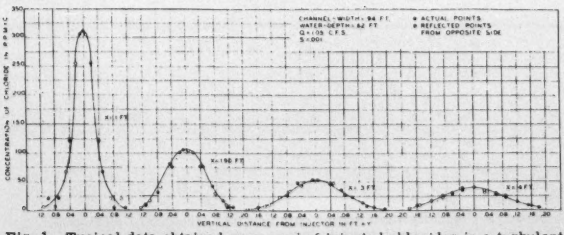
CHANNEL WIDTH: 94 FT.
WATER-DEPTH: 1.62 FT.
Q = 105 C.F.S.
S = .001
ACTUAL POINTS
REFLECTED POINTS FROM OPPOSITE SIDE
CONCENTRATION OF CHLORIDE IN P.P.M.
VERTICAL DISTANCE FROM INJECTOR IN FT. +Y
X = 1 FT
X = 3 FT
X = 6 FT

Fig. 1--Typical data obtained on spread of injected chlorides in a turbulent stream for purposes of determining eddy-diffusion coefficient

where Y is the distance above or below a line through the injector in the direction of flow. To eliminate the constant $(M/\sqrt{2\pi\,\overline{Y^2}})$ let C_0 be the concentration at Y = 0, then we have

$$(C/C_0) = e^{-Y^2/2\,\overline{Y^2}} \tag{9}$$

or

$$\overline{Y^2} = -\,4.606\,\overline{Y^2}\,\log\,(C/C_0) \tag{9a}$$

where the logarithm is to the base 10.

After some experimentation it was decided to inject into the flowing water a mixture of hydro-

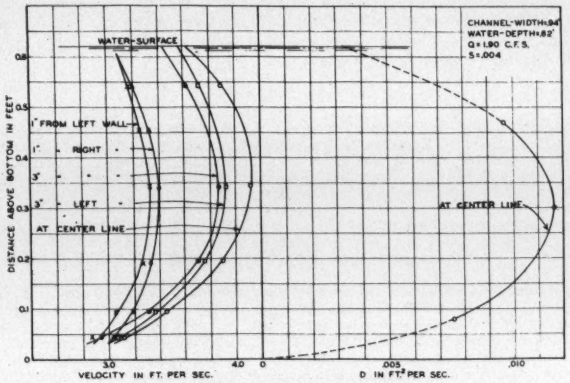

Fig. 2--Velocity-distribution data and measured eddy-diffusion coefficients in a small open channel

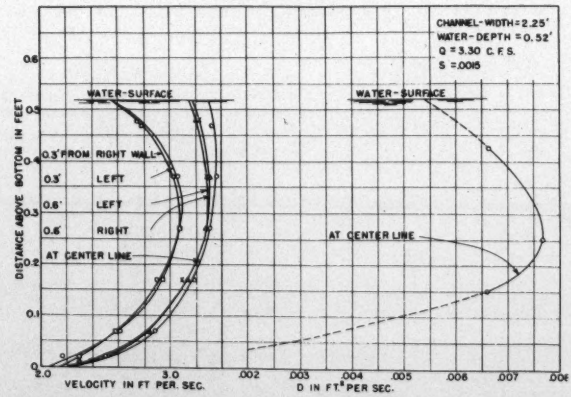

Fig. 3--Velocity-distribution data and measured eddy-diffusion coefficients in larger open channel

chloric acid and alcohol, the proportions being adjusted to give the mixture a density equal to that of the water. This mixture was adopted because it is easy to prepare, it is stable, and it is a very simple matter to determine the concentration of chlorides in water. The procedure was to inject a steady flow of the mixture into the water-stream and to collect samples of the water at various transverse distances Y, at several sections down-stream from the injector. The sampling time was about 1-1/2 to two minutes, thus insuring that the average chloride concentration was obtained at any point. The standard method of water analysis for determining chloride-concentrations in water was used in these studies. Since the water in the channels contained some chlorides it was necessary to continually take a control-sample.

The concentration-ratios, (C/C_0), were plotted against Y for the different sections and a mean curve drawn through the plotted points. According to equation (9) if (C/C_0) is plotted against Y on semi-logarithmic paper a straight line should result whose slope would be $-4.606\ \overline{Y^2}$, thus permitting the determination of $\overline{Y^2}$. Then plotting the various $\overline{Y^2}$-values against x, the values of D could be calculated according to equation (5). In Figure 1 are shown some typical data that were obtained for determining one eddy-diffusion coefficient. Note that, theoretically, according to equation (9) only two samples are really necessary to obtain $\overline{Y^2}$ at any section--one sample at $Y = 0$ and the other at some other value of Y. However, to insure against any error and also to verify that the distribution follows the normal error law about eight to ten samples were taken at each section. The work involved in taking and analyzing the water-samples was not particularly great.

(C) Data on eddy-diffusion coefficient

To obtain some idea of the variation of the eddy-diffusion coefficient in the cross-section of a channel, data were obtained in the two sizes of channels for various depths and slopes of water. Both vertical and horizontal diffusion-coefficients were measured. In the large channel, 2.25 feet wide, data were obtained at the center and at two other verticals, 0.3 foot and 0.6 foot from the wall. The channel-bottoms were kept smooth and also roughened by gluing to the bottom some sand of the size used in the tests of suspended-material transportation. Measurements of diffusion-coefficient were also made during the tests run with sand in suspension.

Since lack of space prohibits presenting all these data, only the general pertinent results obtained will be discussed. In Figures 2 and 3 some velocity-distribution data at several verticals, and vertical diffusion-coefficient data at the center of the channels are shown for the small and large channels, respectively. These particular data were obtained with clean water and the channel-bottoms were roughened by glued sand. Note that the maximum value of D occurs at about the mid-depth. This is quite typical. The value of the vertical diffusion-coefficient must become zero at the bottom; however, it does not necessarily become zero at the free surface, though it may approach zero for very quiet flow.

It was found that the vertical diffusion-coefficients tended to decrease from the center toward the side walls. The horizontal diffusion-coefficients tended to be more uniform from top to bottom; however, they also had a maximum value at the mid-depth. They did not approach zero at the bottom or at the free surface. The horizontal diffusion-coefficients increased from the center toward the quarter-points, and then decreased toward the side walls. They appeared to have a maximum value at the quarter-points of any cross-section. The horizontal coefficients appeared always to be greater than those in the vertical direction. For the same depth and slope the coefficients were larger in the rougher channel, as is to be expected.

The vertical diffusion-coefficient, D, can be compared to the kinematic eddy-viscosity, ϵ, which occurs in the relation between shear and velocity-gradient for turbulent flow

$$\tau = \rho\, \epsilon\, (dU/dy) \qquad (10)$$

where τ is the unit-shear and ρ the fluid density. If the transfer by the turbulence of momentum and of matter is physically identical then D and ϵ should be the same. Experimental verification of this is somewhat hard because of the difficulty in calculating ϵ accurately due to the fact that the shear cannot be obtained with any degree of precision in channels where the side-wall effect is appreciable. Some calculations of ϵ were made for these studies with different assumptions for the value of the shear, and the values obtained for ϵ compared well with the measured values of D. In general our conclusion is that for practical purposes D and ϵ can be considered identical.

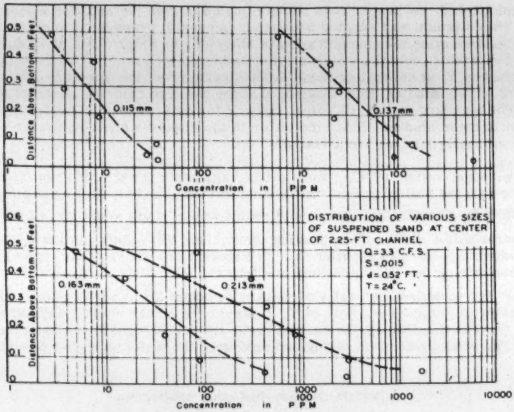
Distance Above Bottom in Feet
0.115 mm
0.137 mm
Concentration in P P M
DISTRIBUTION OF VARIOUS SIZES OF SUSPENDED SAND AT CENTER OF 2.25-FT CHANNEL
Q = 3.3 C.F.S.
S = .0015
d = 0.52 FT.
T = 24°C.
0.163 mm
0.213 mm
Concentration in P P M

Fig. 4--Experimental data on distribution of suspended sand and comparison with theoretical variation

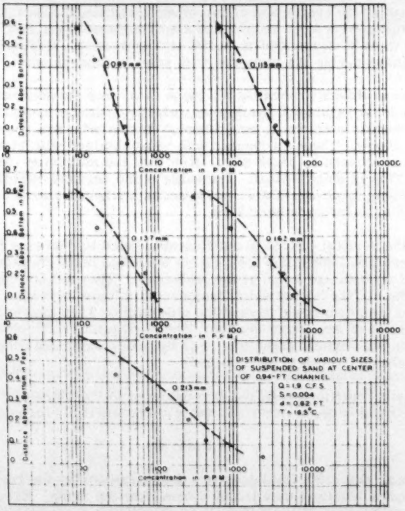

Fig. 5--Experimental data on distribution of suspended sand and comparison with theoretical variation

(D) Suspended-material measurements

These experiments were made with a white "banding" sand having a size ranging from 0.08 to 0.40 mm and the average size being 0.18 mm. In the small, 0.94-foot wide channel the sampling was done a distance of about 60 feet from the entrance to the channel, and for the large, 2.25-foot wide channel the sampling section was about 80 feet from the entrance. Observations indicated that conditions of equilibrium existed at the sampling sections. Every precaution was taken to secure a proper mean sample by withdrawing the water at a point with a fine tube pointing upstream. The intake-velocity was adjusted to equal that of the oncoming flow and the time of withdrawal was about 1-1/2 minutes. Samples were taken at the center-line vertical, and at two verticals on each side of the center-line. About seven samples were taken in each vertical, with closer spacing between samples near the bottom than near the surface.

The total concentration-data indicated that the suspended material near the bottom decreased from the center toward the wall, but near the free surface the reverse was true. Hence the vertical distribution of suspended material near the sides of channel was more uniform than it was farther from the wall.

The point-samples taken at the center vertical in both channels were analyzed to determine the distribution of various sizes. The samples were divided into the following size-ranges, expressed in mm: 0.250 to 0.177, 0.177 to 0.149, 0.149 to 0.125, 0.125 to 0.105, 0.105 to 0.074. The arithmetic mean size was used in all the computations and designations relating to the various size-ranges.

In Figures 4 and 5 are shown some typical suspended material distributions for the different size-ranges as obtained from measurements at the center-lines of the two channels. The two-dimensional analysis [3] for the vertical distribution of suspended material gives the theoretical relation of equation (11).

$$\mathrm{Log_e}\,(N/N_a) = -\,c\int_a^y (dy/D) \qquad (11)$$

where N is the concentration of material having a fall velocity c at a distance y above the bed, N_a is the concentration at distance a, and D is the eddy-diffusion coefficient in the vertical direction. Figures 4 and 5 show the curves plotted using equation (11) where N_a is taken as the measured concentration at one-tenth the depth above the bottom, and D is the coefficient shown in Figures 2 and 3. The integral was evaluated graphically. The values of D used were obtained in clear water with a sand-roughened channel-bottom. Values of D were also measured in the large channel with the suspended material present and were found to be slightly larger, but the sediment-distribution curves calculated from these coefficients were practically identical to those shown in Figure 5. Of course, in general the diffusion-coefficients should be measured with sand in suspension, since an artificially roughened bottom may not be identical to a natural sand-bed.

It thus appears that eddy-diffusion coefficients directly measured by the method outlined herein can be used to predict suspended-sediment distributions. This verifies the validity of Taylor's theory of eddy-diffusion and indicates that we have correctly measured the eddy-diffusion coefficient so far as mass-transfer is concerned. Further work in this direction should include analyses of suspended-sediment distribution at other verticals besides the center, and extension of the theoretical relation of sediment distribution to three-dimensional phenomena. Measurement of the eddy-diffusion coefficients in the horizontal and vertical directions at various points in a stream cross-section will permit a detailed study of suspended-sediment distribution in three dimensions.

A detailed report on which this paper is based was submitted by the junior author as a partial fulfillment of the requirements for a Ph.D. degree in mechanics and hydraulics at the State University of Iowa.

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[3] M. P. O'BRIEN, Review of the theory of turbulent flow and its relation to sediment-transportation, Trans. Amer. Geophys. Union, pp. 487-491, 1933.

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DISCUSSION

J. W. JOHNSON (University of California, Berkeley, California)--The authors' experimental data in addition to the data of other investigators taken in recent years appear to verify, for all practical purposes, the general theory of the vertical distribution of suspended sediment in a turbulent stream of water. This theory permits the total suspended-sediment load transported in a vertical section to be estimated from a determination of the concentration and the particle-size distribution of the sediment at a single point in the vertical, and the hydraulic characteristics of the stream.

The primary purpose of the various investigations on the distribution of suspended sediment is to permit a general procedure to be developed for estimating the total suspended load of any particular stream. Such a method should be easy to apply, accurate, and less costly than the method of taking many samples in a cross-section at frequent intervals throughout a flood. The application of the method to wide rivers (two-dimensional flow), appears to be fairly well established. As mentioned by the authors, future experiments on the distribution of suspended matter should be directed toward a practical solution of problems occurring in three-dimensional flow. Although the authors have made a start in this direction by measuring values of the diffusion-coefficient in various verticals and horizontals in channels of finite width, more extensive experiments appear necessary.

The distribution of velocity in a cross-section is a function of the distribution of shear-force along the boundary. In a channel with a relative high ratio of width to depth the distribution of velocity near the center of the stream is related to the unit-shear at the bed as expressed by equation (10). Near the banks or side walls, however, the velocity-distribution is affected by shear along both the bed and the walls. In this case the distribution of the kinematic eddy-viscosity or the diffusion-coefficient along a vertical, perpendicular to the bed, has little meaning. The distribution of sediment in such a vertical as predicted by equation (11) would not agree with actual measurements. In predicting the distribution of sediment in three-dimensional flow, Leighly [Univ. Calif. Pub. Geog., v. 6, No. 1, p. 14] considered the distribution of the eddy-viscosity coefficient along prisms whose center lines started at points along the bed and continued upward into the flow, perpendicular to each velocity-contour, and terminated at the line of maximum velocity. Equation (11), with the diffusion-coefficient replaced by the eddy-viscosity coefficient, was then used to compute the distribution of sediment along the various prisms. As far as the writer knows, an experimental verification of Leighly's method has not been made. Laboratory investigations to check the method could and should be made. It would be desirable that such experiments be made with a movable bed rather than a fixed bed made rough by gluing sand-grains to the channel-bottom; because, as shown by EINSTEIN [2nd Hydraulic Conference, Univ. Iowa, 1942], the roughness-coefficient differs for a fixed and a movable bed composed of the same material. Einstein also gave experimental evidence to show that, for the movable bed, the roughness-coefficient varies with the rate of bed-load transportation. Laboratory experiments in which bed-load transportation is accompanied by an appreciable suspended load would also be of value in furthering our knowledge of bed-load transportation and permit the range of application of bed-load formulas to be extended to the conditions usually found in natural streams.

FLOW OF FLUIDS THROUGH GRANULAR MATERIAL: FILTRATION, EXPANSION, AND HINDERED SETTLING

Loranus P. Hatch

Introduction--Investigations of the flow of fluids through granular materials generally have been limited to such studies as filtration, ground-water movement, flow of gases through packed columns, etc., in which the fluid passes through an assemblage of stationary particles. There are, however, at least two other phenomena often encountered in engineering practice which appear to be essentially identical to filtration but which have received little or no fundamental consideration. (The term, filtration, as used throughout this paper designates a condition of flow.) These are commonly referred to as "expansion", in which the particles are suspended in an upward-flowing fluid while the particle-column as a whole is stationary, and "hindered settling", in which the particles settle in the fluid with a uniform terminal velocity while the fluid-column remains stationary. In each of these three cases of the general problem of flow through granular materials, the factors which influence the resistance to flow, namely, velocity, particle-size, density, viscosity, and porosity, are essentially the same; hence, a single equation should satisfy the requirements of all three cases.

To simplify matters, the particle-size, the particle- and fluid-densities, and the viscosity,

may be considered constant and all variation centered in the resistance to flow, the porosity, and the velocity. Each of these variables, in turn, is seen to be the principle unknown in problems of filtration, expansion, and hindered settling.

First of all, we shall have made a considerable step toward a rational solution of the problem of flow through granular materials if an analogy to flow in pipes is found to be acceptable. Obviously, the tortuous and irregular flow-channels within granular beds do not resemble in structure the straight and uniform paths defined by a pipe-wall, nor is it necessary to overlook the additional resistance to flow imposed by the constantly changing direction, size, and shape of individual flow-channels. These changing factors, however, follow an orderly cycle within a homogeneous medium, and we are permitted to think in terms of an average channel or system of channels. It is conceivable, therefore, that some linear dimension, characteristic of the size of the average channel, may be shown to fulfill the requirements of a generalized equation of flow which will embrace the three cases of filtration, expansion, and hindered settling. Naturally, the diameter and velocity-factors in pipe-flow are not applicable to the conditions of flow through granular materials without considerable modification.

Filtration--Although filtration has been the subject of many independent investigations, it has generally been studied by the use of empirical methods. In several formulations the diameter-term, or size of flow-channels, is given only in terms of the size of the particles making up the assemblage. Over a wide range of porosity, however, it must be recognized that the size of particle alone is hardly more significant than the thickness of a pipe-wall in pipe-flow. In more recent studies the degree of packing, or porosity, has been introduced either as an independent factor or in combination with the particle-size.

Among the purely empirical equations, the best known is the one developed by ALLEN HAZEN [see 1 of "References" at end of paper] which introduced the principle of an "effective particle-size". The effective size as described by Hazen was found through experiment to bear a fairly consistent relation to the resistance to flow, under certain conditions of packing, and is seen to be not only a measure of particle-size but of porosity as well. Consequently, the effective size is useful only with non-stratified packings wherein a change in the particle-size distribution or "uniformity-coefficient" gives also a change in the normal porosity of the assemblage. Other equations for filtration contain similar effective-size factors and are essentially modifications of Hazen's equation.

BLAKE [2], in 1922, is believed to have been the first to recognize the importance of particle-surface-area concentration as a measure of the size of flow-channels in assemblages of granular materials. His direct substitution of surface-area of particles per unit of free space in place of the diameter-term as used in pipe-flow, although not rationalized, led to a very satisfactory equation which may be expressed as in equation (1).

$$h\, a^3/\ell\, v^2\, (A/V)\, (1 - a) = \text{function}\ v\, r/(A/V)\, (1 - a)\, u \qquad (1)$$

where h = resistance head in terms of fluid column, a = porosity, or free volume divided by total packed volume, ℓ = length of packing, v = average velocity, or rate of discharge per unit of gross area of packing, r = density of fluid, u = viscosity of fluid, A = surface-area of particles, and V = volume of particles.

KOZENY [3], in 1927, and FAIR and HATCH [4], in 1933, working independently, derived equations for flow through granular materials in which the diameter-term is expressed as the surface-area of solids per unit of free volume. The two equations are largely identical to Blake's equation and both are based on the pipe-flow analogy. Kozeny's equation in its present form is limited in scope in that it is applicable only to laminar flow with materials of uniform size, and makes no provision for stratification of packing. The equation of Fair and Hatch is directly related to the pipe-flow equation through the hydraulic radius as a measure of inter-channel diameter, and is general in scope and applicable to both stratified and non-stratified packings. Thus, if n is the state-of-flow factor, k is a coefficient, and g is the gravity-constant, then

$$(h/\ell) = (k/g)\, (u/r)^{(2-n)}\, v^n\, (A/V)^{(3-n)}\, (1 - a)^{(3-n)}/a^3 \qquad (2)$$

For non-stratified packing,

$$A/V = (S/100)\ \Sigma\ (P/d) \qquad (2a)$$

For stratified packing,

$$(A/V)^2 = (S^2/100)\ \Sigma\ (P/d^2) \qquad (2b)$$

where P is weight-percentage of material of uniform size d and S is shape-factor.

The author [5] has presented experimental evidence covering a considerable range of particle-size, distribution of sizes, and particle-assemblage to verify equations (2), (2a), and (2b). In this study, well-rounded sand-grains having substantially the same shape were used in all tests and, therefore, the numerical effect of particle-shape is not included in the values of the coefficients of the equation.

SLICHTER [6] and, more recently, GRATON and FRASER [7] have analyzed the geometry of ideal assemblages of uniform spheres with a view to establishing a direct measure of the size of flow-channels in terms of the diameter of the sphere, together with a mathematical description of the arrangement of the spheres in space. Although this approach is direct, it may well serve to discourage further similar investigation through sheer emphasis on the maze of geometric packings to be encountered in nature. The most recent attempt to evaluate the inter-channel velocity and characteristic diameter, familiar to the author, is that of BAKHMETEFF and FEODOROFF [8]. That attempt is founded on the significance of dimensional consistency in the use of porosity in combination with particle-size and the cross-sectional area of the inter-channel voids. As pointed out by the author [5,9], the analysis of Bakhmeteff and Feodoroff is not rational, largely because the authors consider porosity to be a volumetric or three-dimensional parameter, whereas it is simply a dimensionless quantity measured by the ratio of void-volume to total packed volume, or, with a constant depth, by the ratio of open area to gross area in a cross-section.

Expansion--In the beginning of this paper it is stated that flow in expansion, with the particles suspended in an upward-flowing fluid, is governed by the same laws as flow in filtration. In expansion, however, the particles do not remain stationary but are continually in a state of motion, milling about at random or undergoing orderly circulatory movement. With stabilized conditions of flow and temperature, however, the expanded column will continue to occupy a constant volume. Except for small inequalities due to unbalanced local fluid-currents, moreover, it may be assumed that the distribution of particles of the same size and density will be substantially uniform in the assemblage. The significance of individual measurements in studying expansion, therefore, will be the same as in studying filtration, although it may well be argued that the motion of individual particles in expansion will impose additional energy-losses and thereby introduce a new variable into the general flow-equation. For all practical purposes, however, additional losses appear to be either non-existent or not measurable for the following reasons: (1) Resistance to flow in stabilized expansion is equal to the weight of the particles in the fluid, regardless of the degree of expansion; (2) greatly increased circulatory motion of an entire assemblage of particles, brought about by tipping the experimental apparatus (usually a glass tube) from its vertical position, does not alter the degree of expansion.

Assuming that expansion is merely a particular case of the general problem of fluid-flow through granular materials, FAIR and HATCH [4] presented an equation for expansion which is simply a restatement of equation (2). That derivation, in which resistance is equated to the weight of the particles in the fluid, is briefly

$$(h/\ell) = [(r_s - r)/r)\ (1 - a)]$$

where r_s = particle-density, or

$$[a^3/(1 - a)^{(2-n)}] = [(k/g)\ (u/r)^{(2-n)}\ v^n\ (A/V)^{(3-n)}]\ [r/(r_s - r)] \qquad (3)$$

In filtration, the influence of porosity can be measured experimentally only in a narrow range without altering the particle-size distribution. Equations for filtration, therefore, may be examined to advantage under conditions of flow in expansion, since in the latter case the essential difference would be confined to much larger values of porosity. Hence, the validity of a porosity-factor tested in filtration will be greatly enhanced if it can be shown to fulfill also the requirements of flow in expansion. The equation of Bakhmeteff and Feodoroff [8], for example, falls short of the desired result in this respect as shown in the following analysis:

$$(h/\ell) = \text{constant}\ \ (v^n/2g)\ (u/r)^{(2-n)}\ d^{(n-3)}\ [1/a^{(n+3)/3}]$$

where d = particle-diameter, or, for n = 1.0

$$[(1 - a)\ a^{4/3}] = \text{constant}\ (v/2g)\ (u/r)\ (1/d^2)\ [r/(r_s - r)]$$

Table 1--Porosity and fluid-velocity in expansion-tests

Column height	Porosity, a	$\frac{a^3}{(1-a)}$	Velocity	Temperature	Column height	Porosity, a	$\frac{a^3}{(1-a)}$	Velocity	Temperature
inch			cm/s	°C	inch			cm/s	°C
				(A) Sand No. 48-60 mesh per inch					
16.4	.680	0.983	.570	18.0	17.0	.692	1.074	.836	35.0
14.7	.643	0.744	.429	18.0	16.5	.684	1.013	.800	35.0
13.5	.613	0.595	.337	18.0	14.3	.634	0.696	.579	35.0
12.9	.593	0.511	.283	18.0	13.7	.617	0.613	.493	35.0
12.5	.580	0.464	.264	18.0	13.0	.596	0.524	.429	35.0
11.8	.555	0.383	.205	18.0	12.6	.584	0.478	.386	35.0
11.1	.529	0.314	.163	18.0	12.0	.565	0.415	.327	35.0
10.7	.511	0.273	.143	18.0	12.5	.582	0.471	.386	35.2
9.7	.460	0.180	.0953	18.3	12.4	.577	0.454	.369	35.0
16.1	.675	0.946	.557	18.3	12.3	.573	0.440	.356	35.0
16.5	.682	0.996	.583	18.2	11.5	.545	0.355	.278	35.0
16.7	.687	1.037	.613	18.2	15.3	.658	0.833	.676	35.0
15.6	.665	0.879	.521	18.2	14.1	.630	0.675	.549	35.0
17.1	.694	1.092	.634	18.3	14.0	.627	0.661	.540	35.0
17.8	.706	1.196	.695	18.3					
18.2	.712	1.252	.716	18.0	15.9	.671	0.918	.960	47.0
18.9	.723	1.364	.767	18.3	13.9	.624	0.645	.672	47.2
19.6	.733	1.474	.824	18.2	13.4	.610	0.581	.626	47.2
10.7	.511	0.273	.138	18.0	12.8	.592	0.508	.522	47.0
10.3	.492	0.235	.115	18.0	12.8	.592	0.508	.540	47.1
10.1	.482	0.217	.104	18.0	12.1	.569	0.427	.446	47.2
10.2	.488	0.227	.112	18.0	11.2	.533	0.324	.328	47.0
					13.9	.624	0.645	.695	47.0
16.5	.682	0.996	.665	22.9	12.9	.595	0.520	.557	47.0
16.4	.680	0.983	.650	22.9					
17.1	.693	1.084	.703	22.9	14.0	.625	0.651	.695	47.0
12.2	.570	0.431	.279	22.9	11.6	.550	0.370	.372	46.6
11.4	.540	0.342	.214	22.9	12.4	.579	0.461	.483	46.8
10.4	.498	0.246	.149	22.9	13.2	.603	0.552	.605	47.0
9.8	.466	0.190	.117	22.9	12.0	.565	0.415	.456	47.1
10.4	.498	0.246	.150	23.0	15.7	.667	0.890	.973	47.0
10.1	.482	0.217	.133	23.0	12.1	.566	0.418	.456	47.0
14.5	.638	0.716	.482	23.0	11.3	.538	0.336	.361	47.2
13.3	.605	0.560	.368	23.0	11.5	.545	0.355	.390	47.0
12.9	.595	0.520	.332	23.3	10.5	.502	0.254	.250	46.6
12.4	.577	0.454	.292	23.2					
11.8	.557	0.390	.244	23.2	13.1	.601	0.544	.730	62.5
11.3	.535	0.329	.200	23.2	14.1	.629	0.670	.924	62.5
15.7	.666	0.883	.592	23.2	14.4	.636	0.706	.901	62.5
16.6	.685	1.020	.679	23.2	12.8	.590	0.500	.648	62.5
					11.9	.560	0.399	.525	62.8
17.2	.696	1.109	.730	23.2	11.3	.538	0.336	.426	62.4
17.7	.705	1.189	.768	23.0	10.7	.511	0.273	.348	62.5
15.0	.652	0.795	.530	23.0					
12.9	.595	0.520	.336	23.0					
11.9	.559	0.396	.244	23.0					
11.8	.592	0.508	.325	23.0					
15.0	.652	0.795	.521	23.0					
14.4	.637	0.711	.473	23.1					
13.2	.604	0.556	.365	23.1					
13.0	.598	0.532	.347	23.0					
11.4	.539	0.339	.206	23.0					
13.8	.621	0.631	.415	23.0					
14.9	.649	0.778	.521	23.0					
15.7	.667	0.890	.583	22.8					
16.1	.676	0.953	.634	22.9					

Note: Values of average coefficient in equation (3), not including numerical shape-factor, with 48-60 well-rounded sand; mean diameter (measured) = 0.359 mm:

18.0 C	k = 333
23.0	328
35.0	349
47.0	325
62.5	345

From this relation one may deduce that in expansion large increases in the porosity would require only small increases in the velocity of flow, and for porosity above 57 per cent, even smaller velocities would cause the assemblage to be lifted to greater heights.

At the time Fair and Hatch presented their equation (3) they were not prepared to submit experimental data to substantiate the theoretical conclusions. This was due, in part, to inadequate measurements of the value of the state-of-flow factor, n, which must be known before equation (3),

Table 1--Porosity and fluid-velocity in expansion-tests--Concluded

Column height	Porosity, a	$\frac{a^3}{(1-a)}$	Velocity	Temperature	Column height	Porosity, a	$\frac{a^3}{(1-a)}$	Velocity	Temperature
inch			cm/s	°C	inch			cm/s	°C
			(B) Sand No. 48-100 mesh per inch						
18.9	.716	1.294	.466	24.0	10.6	.494	0.238	0.0735	24.0
14.2	.622	0.636	.220	24.0	11.3	.525	0.304	0.0971	24.0
15.1	.645	0.755	.276	24.0	18.5	.710	1.233	0.463	24.0
16.6	.677	0.961	.360	24.0					
17.6	.695	1.100	.416	24.0	19.6	.710+	1.230	0.584	38.0
18.4	.708	1.216	.465	24.0	17.4	.674	0.940	0.462	38.0
15.4	.652	0.795	.295	24.0	16.3	.652	0.795	0.389	38.0
14.1	.620	0.627	.226	24.0	15.2	.626	0.655	0.321	38.0
18.7	.713	1.263	.465	24.0	14.8	.616	0.608	0.291	38.0
16.7	.679	0.974	.359	23.8	14.1	.597	0.528	0.259	38.0
16.3	.671	0.918	.331	24.0	13.6	.583	0.475	0.219	38.0
12.6	.574	0.444	.146	23.5	12.6	.550	0.370	0.167	38.0
14.7	.635	0.701	.258	24.0	14.7	.614	0.599	0.284	38.0
16.3	.671	0.918	.336	23.9	14.3	.603	0.552	0.282	38.0
13.8	.612	0.590	.206	23.9	13.5	.580	0.464	0.234	38.0
13.1	.590	0.500	.171	24.0	19.6	.710	1.233	0.577	38.0
15.2	.647	0.766	.278	24.0	18.3	.690	1.060	0.502	38.0
16.1	.667	0.890	.325	24.0	17.1	.668	0.899	0.434	38.0
17.4	.692	1.074	.390	24.0	17.1	.668	0.899	0.432	38.0
18.3	.707	1.206	.457	24.0	15.8	.641	0.732	0.357	37.8
18.8	.713	1.263	.443	23.8	14.3	.603	0.552	0.266	38.0
17.6	.695	1.100	.411	23.8	17.5	.676	0.953	0.463	38.0
18.4	.708	1.216	.443	23.8					
19.0	.718	1.313	.471	23.6	19.6	.710	1.230	0.788	60.1
20.5	.738	1.533	.540	23.6	17.7	.680	0.983	0.645	60.0
16.1	.667	0.890	.318	23.7	17.4	.674	0.940	0.627	60.0
14.2	.622	0.636	.219	23.9	16.9	.664	0.871	0.591	60.0
12.8	.580	0.464	.154	23.9	16.6	.658	0.833	0.559	60.0
14.1	.620	0.627	.233	24.1	15.5	.634	0.696	0.469	59.8
12.1	.557	0.390	.130	24.1	14.8	.616	0.608	0.414	60.2
12.0	.553	0.378	.124	24.0	13.8	.589	0.497	0.328	60.0
11.9	.550	0.370	.121	24.2	Note: Mean diameter not determined for computation of coefficients (k).				
10.6	.494	0.238	.0750	24.0					
			(C) Sand No. 100-200 mesh per inch						
4.3	.818	3.010	.271	28.3					
4.8	.837	3.600	.311	28.3					
5.3	.852	4.180	.357	28.3					
5.3	.852	4.180	.348	28.3					
2.9	.730	1.440	.122	28.3					
2.4	.674	0.940	.084	28.0					
2.0	.609	0.577	.045	28.0					
4.2	.814	2.900	.257	28.0					
4.1	.809	2.770	.248	27.8					
4.8	.837	3.600	.305	27.6					
4.7	.833	3.460	.302	27.6					
5.2	.850	4.080	.340	27.8					
4.5	.826	3.240	.284	27.8					
3.8	.795	2.450	.225	27.6					
3.3	.763	1.870	.172	27.6					
3.2	.756	1.770	.164	27.6					

Porosity, a	$\frac{a^3}{(1-a)}$	Velocity	$v^{1.7}$	Temperature
		cm/s		°C
		(D) Sand No. 20-28 mesh per inch		
.727	0.567	3.70	9.247	20.9
.747	0.630	3.96	10.42	20.9
.762	0.680	4.23	11.70	21.0
.772	0.716	4.30	11.94	21.0
.788	0.779	4.75	14.16	21.2
.810	0.875	5.02	15.52	21.3
.864	1.174	5.83	19.19	21.0
.877	1.264	6.10	21.58	21.0
.834	0.995	5.20	16.52	20.8

+Weight of sand changed from 615 gm to 653 gm.

as well as any other flow-equation, can be set up in useful form. To one who observes an assemblage of particles in expansion, as in the back-washing of an experimental walter-filter, for example, it may well appear that the fluid-flow must be turbulent to an appreciable degree, with values of n considerably greater than 1.0. This is frequently not the case, however, for it can be shown that laminar flow, or its equivalent in so far as resistance is concerned, may prevail with assemblages of sand grains up to at least 0.4 mm in diameter expanded in water to porosities as high as 70 per cent. Of course, the fluid does not move in straight parallel lines as in laminar flow in pipes, but is forced to follow irregular paths because of the interference set up by the particles in suspension. This is an exterior influence, however, not caused by inadequate viscosity-forces, and it does not appear to change the inherent flow-characteristics. A somewhat

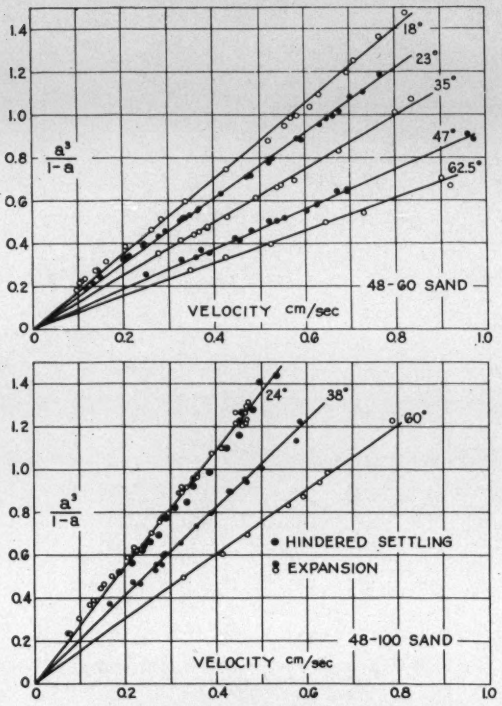

Fig. 1--Relation of porosity and velocity in expansion and hindered settling

similar condition in pipe-flow is reflected in the abrupt bending of stream-lines, marked by a dye-stream, to conform to the outline of stationary solids suspended in the pipe. The state of flow in expansion, moreover, is not to be considered in the light of Stokes' law of freely falling bodies in accordance with which only sand-particles smaller than roughly 0.1 mm would be expected to invoke a condition of laminar flow in water. In free fall, the displaced fluid moves past the particles through a relatively large area, whereas in expansion the flow-channel is closely confined by the surrounding particles, thus giving the effect of a small diameter-term in the Reynolds' number. The state of flow in a particular range of expansion, or the value of n in equation (3), may be determined independently from the relationship of the velocity- and temperature-factors, with all other variables including porosity held constant. Or, $(u/r)^{(n-2)} = \text{constant} \times v^n$. This method of evaluating n was used by the author throughout the present study and the data shown in Table 1, with the exception of the 20- to 28-mesh sand-tests, lies within the range of flow where n equals 1.0 or a reasonably close approximation. The values are shown plotted in Figures 1 and 2 in terms of $[a^3/(1 - a)]$ and v, in accordance with equation (3). For the larger 20- to 28-mesh sand, the value of n was found to be about 1.7 and the results of expansion are plotted in Figure 2 in terms of $[a^3/(1 - a)^{0.3}]$ and $v^{1.7}$. The values of the coefficients in equation (3) relative to expansion, with n = 1, were found to agree reasonably well with those determined by the author [5] from the results of filtration-tests.

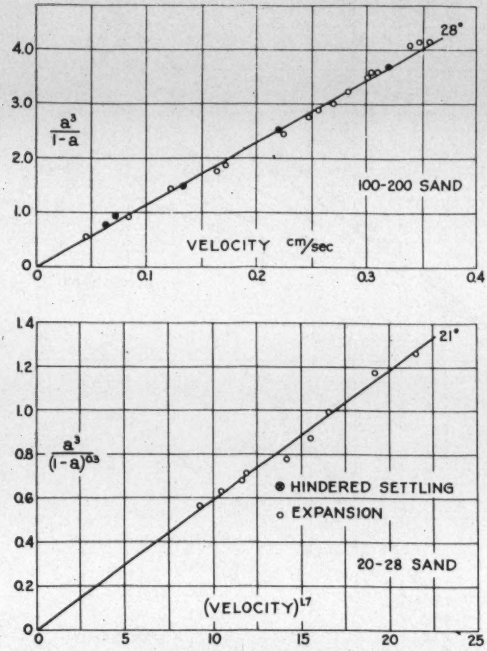

Fig. 2--Relation of porosity and velocity in expansion and hindered settling

Further evidence to substantiate the author's evaluation of n in expansion-tests is to be found in Figures 3 and 4 which show the course of dye-streams in upward-flowing water, with the dye discharged in each case at a point just above the top of the expanded sand-column. Although this cannot be considered a direct measure of the state of flow within the sand-column itself, there is good reason to believe that disturbances caused by turbulence in the channel-ways between the particles would be projected for some considerable distance into the otherwise undisturbed water-way above. The introduction of slight turbulence as indicated in Figure 4 was clearly in evidence through excessive fluid-drag on the particles resulting in abnormal values of porosity.

The apparatus for measuring expansion consisted of a glass tube about 1.8 inches in diameter and five feet long, with graded coarse material at the bottom for dispersing the flow and separated from the expanded column by means of a wire screen. Distilled water was used in all tests and the tube was insulated by means of asbestos tape and wound with resistance wire. With controlled electrical heating, constant temperatures were maintained throughout the length of the tube during the course of a complete test. Readings were recorded only after the expanded column had become stabilized.

The author has not been successful in attempts to derive a single equation for the expansion of non-uniform material. In this case the individual size-fractions would be stratified with the coarsest at the bottom and the finest at the top, but each fraction would show a different porosity and possibly a different state of flow. A summation of the expanded heights of the size-layers was proposed by FAIR and HATCH [4] for calculating the degree of expansion of non-uniform material.

Fig. 3--Dye-stream indicating laminar flow immediately above expanded sand-column

Fig. 4--Dye-stream indicating turbulence immediately above expanded sand-column

Hindered settling--The behavior of individual particles settling through a quiescent fluid must be considered in the light of two general conditions, namely, settling in "free fall", and "hindered settling". In free fall, the displaced fluid moves upward past a particle through a relatively large area and is not restricted through friction or otherwise opposed by the presence of other bodies or particle-surfaces in the vicinity. Under these conditions of settling one would apply the well-known laws of STOKES, ALLEN, or NEWTON, for falling bodies moving in viscous media.

In hindered settling, on the other hand, the particles would be spaced relatively close to one another in the assemblage and the fluid moving past a given particle would be confined within a space equivalent to a single unit channel-way between particles. The closer the spacing, of course, the greater the tendency to oppose the fluid-flow, not only by decreasing the open area normal to the axis of flow but also by increasing the frictional drag as a result of a greater concentration of particle-surfaces. It follows, therefore, that in hindered settling the degree of packing, which we choose to call porosity, has a twofold effect in restricting the fluid-flow and, similarly, in decreasing the settling-velocity of the particles. In free fall, with the particles widely separated, the influence of porosity is not measurable; its value in this case may be taken as 1.0.

Since the settling of particles is always accompanied by an equal upward displacement of the fluid, the conditions of flow in the channel-ways between the particles would appear to be the same

Table 2--Porosity and terminal velocity in hindered settling-tests

Initial column-height	Porosity, a	$\frac{a^3}{(1-a)}$	Velocity	Temperature
inch			cm/s	°C
(A) Sand No. 48-100 mesh per inch				
17.0	.666	0.883	.322	24.0
20.8	.727	1.41	.496	24.0
15.1	.624	0.645	.243	24.0
19.8	.714	1.27	.456	24.0
18.5	.693	1.08	.389	24.0
16.5	.656	0.821	.310	24.0
14.8	.616	0.608	.223	24.0
16.1	.648	0.773	.287	24.0
19.5	.709	1.23	.451	24.0
14.9	.619	0.622	.225	24.0
17.3	.672	0.924	.351	24.0
17.5	.676	0.953	.351	24.0
16.1	.648	0.773	.290	24.0
15.2	.627	0.661	.259	24.0
19.9	.715	1.28	.481	24.0
18.6	.695	1.10	.423	23.5
21.0	.730	1.44	.535	24.0
19.0	.702	1.16	.453	24.0
17.7	.680	0.983	.387	24.0
16.7	.660	0.845	.338	24.0
15.5	.634	0.696	.276	24.0
14.9	.620	0.627	.238	24.0
14.4	.606	0.565	.216	24.0
14.0	.595	0.520	.188	24.0
(B) Sand No. 100-200 mesh per inch				
3.9	.799	2.54	.221	28.0
4.9	.840	3.70	.321	28.0
3.0	.734	1.49	.134	28.0
2.4	.674	0.940	.072	28.0
2.2	.652	0.795	.063	28.0

whether the particles move downward without acceleration through a quiescent fluid, or are held in suspension with upward flow. It follows, therefore, that in these two cases of flow through granular materials, hindered settling and expansion, the relative movement of particle and fluid is essentially the same. Consequently, we may conclude that one equation will satisfy the requirements of both cases. The author submits, therefore, that equation (3)[v now becomes settling velocity] expresses the essential relationships in hindered settling as well as in expansion.

Terminal velocities in hindered-settling tests with different degrees of packing, measured by porosity, are shown inTable 2 and the values are plotted in Figures 1 and 2. The settling-tests for each size of material were run directly after the expansion-tests and the experimental set-up in each case was the same in all respects. In each test the terminal settling-rate remained constant throughout the period of fall, and was found to closely approximate the average upward velocity of flow in the open tube during expansion. The experimental procedure followed was to stop the flow abruptly with particles in stabilized expansion, and measure the terminal rate of fall by observing the top of the sand column.

With material of non-uniform size the problem of hindered-settling rates becomes much more complicated. Not only would the particle-size distribution and porosity be expected to change as the settling progressed but the fine particles might well be carried upward in currents set in motion by the settling of the large particles. Such upward movement of small particles may explain, in part, the difficulty of removing the "fines" in plain settling-processes.

Among several independent studies of hindered settling which the author has reviewed in the literature, the analysis of WORK and KOHLER [10] is particularly subject to comment in the light of the present study. Briefly, that analysis is based on the following reasoning: That the resistance to upward fluid-flow between the particles is directly related to the arithmetic difference in the settling-rate of the particles in hindered settling as compared with the rate of fall of the same particles in free fall.

In the author's opinion, the resistance to upward fluid-flow is a direct function of settling-rate either in free fall or in hindered settling. The difference in the two rates appears to have no fundamental significance, therefore, and its introduction into the analysis would seem to confuse rather than clarify any rational approach to the problem.

The experimental results recorded in this paper were obtained while the author was employed in the Department of Health and Safety of the Tennessee Valley Authority.

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DISCUSSION

BORIS A. BAKHMETEFF and NICHOLAS V. FEODOROFF (Columbia University, New York, New York)--The author is well justified in intimating that a reliable method for determining the eventual rate of flow through granular media reverts to a comprehensive appraising of the possible effect of porosity. The remarks which follow will be confined to the case of filtration. This indeed is the most important practical case. Moreover, it is comparatively simple and can be best checked against experimental evidence.

The author refers to two methods of evaluating the resistance, which take account of the effect of porosity:

(1) The formula proposed in 1927 by KOZENY, and subsequently worked out independently by FAIR and HATCH, which within the boundaries of the Darcy Law reads (in equation (1) and subsequently ν designates the kinematic viscosity)

$$(h/\ell) = (v\,\nu\,/d^2\,2g)\,[k\,(1 - a)^2/a^3] \qquad (1)$$

(2) The approach, suggested by the writers, according to which

$$(h/\ell) = (v\,\nu\,/d^2\,2g)\,[c_p/a^{4/3}] \qquad (2)$$

As seen, both expressions consist of an identical group ($v\,\nu\,/2g\,d^2$), multiplied by bracketed expressions which besides an appropriate numerical constant (k and respectively c_p) contain the porosity-factor a in different combinations. The respective bracketed group can be appropriately termed the porosity-functions F (a). To make clear what the latter actually mean, when reduced to numerical terms, the quantities

$$F\,(a)_{F\text{-}H} = 358\,[(1 - a)^2/a^3] \quad \text{and} \quad F\,(a)_{B\text{-}F} = (710/a^{4/3}] \qquad (3)$$

have been plotted in Figure 1 versus the porosity, with the constants as indicated. As seen, the formula of Kozeny and of Fair and Hatch makes the eventual influence of porosity quite pronounced. In fact, within the rather narrow limits of 36 per cent $\leq a \leq$ 42 per cent, constituting the customary practical range, the function of Fair and Hatch shows a variation of over 90 per cent, while the curve of Bakhmeteff and Feodoroff indicates a change of less than 25 per cent.

The Kozeny theory was based on certain hypothetical assumptions relating to the possible mechanism of resistance. The semi-empirical attack by Bakhmeteff and Feodoroff simply invoked dimensional reasoning. The arguments relating to the different approaches have been presented elsewhere [8,9,5]. Naturally, the final probe for any suggested formula is its compliance with experimentally observed facts. Numerous experiments at the Fluid Mechanics Laboratory of Columbia University and a careful digest of scores of data obtained by other observers, lead the writers to believe that the influence of porosity on the eventual resistance is not as pronounced as suggested by equation (1). On the other hand, when plotted in unified dimensionless terms, most of the data appeared to range well around the average curve, corresponding to equation (2) and presented in Figure 1 as No. 2. [The latest and most complete summary is to be found in a paper by

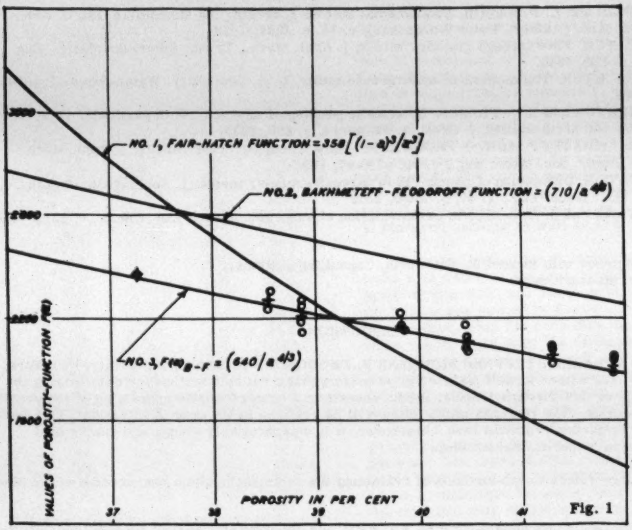

Fig. 1

the writers presented to the Fifth International Congress of Applied Mechanics in 1938 at Cambridge, Massachusetts (Proc., p. 555).]

Most of the previous research, used for establishing curve No. 2, was carried out with water. It is well known that serious difficulties arise in this case because of the air-bubbles, which disengage from the fluid in the course of its motion through the packed solids, and tend to obstruct the pore-openings in an unpredictable manner. Many observers have tried to remedy the situation by using artificially de-aerated water.

Such means, however, are only partly successful, and even the most reliable work such, for example, as that of LINDQUIST [8, 9] furnishes considerably scattered points.

In an endeavor to eliminate such uncontrollable factors, special experiments were carried out more recently at Columbia by measuring resistance offered by packs of uniform lead-shot to a stream of air. As one could expect, the scattering was greatly reduced. In fact, the values of $F(a) = (h/\ell)\,(2g\,d^2/v\nu)$ calculated from the observed data ranged very satisfactorily along curve No. 3, corresponding to the porosity-function, equation (2), of Bakhmeteff and Feodoroff, the only difference being that the constant, $c_p = 640$, proved to be about ten per cent less than the previously suggested $c_p = 710$. (The individual points obtained by Feodoroff and partly by Mr. Lomb are plotted in circles; average values are indicated by crosses.) To show that this difference is due primarily to air-bubbles, a special set of observations were made using water which had remained undisturbed in a tank for a period of a few months. The points obtained with such naturally de-aerated water fell in quite close to those obtained with air. However, most characteristically when the experiments were repeated after having the same water circulate in the system a day or two, the observed values returned to the old range of $c_p = 710$.

Against the experimental evidence, assembled in the Columbia Research, there stand the observational data presented by Mr. HATCH [5]. It is only fair to state that the computed values of the porosity-function based on these latter data, fall in very closely with the curve No. 1 of Fair and Hatch as presented in the Figure. The only conclusion to be drawn in the presence of such circumstances is that before reaching any final decision further and most careful experimental research is indispensable.

Perhaps it should be mentioned in this connection that, generally speaking, the Kozeny prototype did not reach as high a commendation in European literature [11] as it seemingly has enjoyed with American writers. In fact, the most recent monograph on ground-water streaming by DACHLER [12], for some reason or other, fails to make any mention of equation (1).

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A METHOD FOR DETERMINING TRANSMISSIBILITY- AND STORAGE-COEFFICIENTS BY TESTS OF MULTIPLE WELL-SYSTEMS

L. K. Wenzel and A. L. Greenlee

(Published with the approval of the Director of the Geological Survey, United States Department of the Interior)

Introduction

Ground-water has long been recognized as one of our important natural resources, but only in about the last 20 years has concentrated effort been made to place ground-water hydrology on a quantitative basis. The quantitative approach to ground-water work has been brought about largely through the leadership of O. E. MEINZER, Chief of the Ground-Water Division of the Geological Survey, United States Department of the Interior, who has originated and applied many quantitative methods himself, and who has consistently fostered and encouraged this method of attack by his coworkers. That this effort has been ably directed and especially fruitful is shown by the vast number of important ground-water problems relating to the water-supplies for war activities that have been worked out by means of quantitative methods in the last few years.

Most quantitative methods of studying ground-water problems involve the determination of the amount of water that will percolate through formations and the amount of water that the formations will yield when the water-table or artesian head is lowered. These hydrologic properties of formations are usually referred to as transmissibility- and storage-coefficients and are defined, respectively, as (1) the quantity of water, in gallons a day, that will percolate through a strip of the formation one mile wide under a gradient of one foot to a mile, and (2) the quantity of water, in cubic feet, that each vertical column of the formation with a base one foot square will yield as the water-table or piezometric surface declines one foot.

Several successful methods for determining transmissibility- and storage-coefficients have been devised and tested in the laboratory and field, but of these methods, those that utilize the effect on the water-table or artesian head of the discharge of wells under controlled conditions are probably the most generally applicable to field-conditions and are thus most widely used at the present time. These discharging-well methods, and modifications and adaptations of them, have been somewhat arbitrarily segregated into "equilibrium-methods" and "non-equilibrium methods", according to whether each depends on the cone of depression reaching an approximate equilibrium form.

The non-equilibrium formula for computing the draw-down of the ground-water level at any time and place on the cone of depression, which was presented by C. V. THEIS before the Section of Hydrology in 1935, has since been sufficiently tested to show that it is applicable to field-conditions within the practical limitations set down by THEIS, WENZEL, JACOB, GUYTON, and others. It has also been used successfully for determining transmissibility- and storage-coefficients from discharging-well tests. As the formula includes a form of the exponential integral and two unknown factors, the coefficients cannot be computed directly, but must be determined by graphical methods. At the meeting of the Section of Hydrology in 1940, C. E. JACOB described the graphical methods as they are applied to the draw-down of the ground-water level caused by the discharge of a single well. The present paper describes an extension of the graphical methods to draw-downs caused by the discharge of several wells operated at different rates and for different lengths of time.

The draw-down of the piezometric surface at any time and at any place on the cone of depression caused by a discharging well is given by the non-equilibrium formula [see 1 of "References" at end of paper]

$$s = 114.6\,(q/T)\int_u^{\infty} (e^{-u}/u)du$$

where $u = (1.87r^2S/Tt)$ and s is the draw-down (in feet) at any point in the vicinity of a well discharging at a uniform rate, q is the discharge of the well (in gallons a minute), T is the coefficient of transmissibility of the aquifer (that is, the discharge under a unit-gradient, in gallons a day, through each strip one foot wide and extending the height of the aquifer), r is the distance (in feet) of the discharge-well to the point of observation, S is the coefficient of storage, as a decimal fraction (cubic feet of water discharged from each vertical column of the aquifer with a base one foot square as the water-level declines one foot), and t is the time the well has been operating (in days).

The value of the integral is given by the series

$$\int_u^\infty (e^{-u}/u)du = -0.577216 - \log_e u + u - u^2/2\cdot 2! + u^3/3\cdot 3! - u^4/4\cdot 4! \ldots$$

The formula may be used in two ways. If the coefficients of transmissibility and storage are known, the draw-down can be computed directly for any time and any point on the cone of depression. If the draw-downs are known, the coefficients of transmissibility and storage can be determined by graphical methods. If the draw-downs are known, T and S can be determined (1) from the draw-down curve of one well--that is, from the form of the draw-down curve--or (2) from the draw-downs that are observed at any one time in a line of wells--that is, from the form of the cone of depression.

The formula cannot be solved directly for T and S. However, T and S can be determined conveniently by the following graphical method that was devised by THEIS [2] and described later by JACOB [3]. The non-equilibrium formula may be written

$$s = (114.6\ q/T)W(u)$$

where $u = (1.87r^2S/Tt)$, in which W(u) may be read as "well-function of u", and the other terms as previously defined.

When T and S are to be determined from observations on the draw-down in one well, the log of the draw-down is plotted against the reciprocal of the log of the time since pumping began. When T and S are to be determined from the draw-downs in a line of wells, the log of the draw-down is plotted against log (r^2/t). If the formation were entirely homogeneous and isotropic and the water were discharged from the formation instantaneously with the fall in head, all points so plotted, for all times and all wells, would fall on a smooth curve. The curve so determined is a segment of a type-curve produced by plotting the log of the value of the integral, W(u), against log of the quantity u. If, therefore, (1) the type-curve is plotted on logarithmic paper and (2) the observed draw-down values are plotted on transparent paper against (1/t) for one observation-well, or (r^2/t) for a line of observation-wells, to the same logarithmic scale as that used for plotting the type-curve, (3) the observed curve can be fitted to the type-curve in only one place. Then (4) from this fit the value of W(u) and the corresponding value of u may be determined from the type-curve for any selected point on the curve, which (5) may be used in conjunction with the observed values for that point to determine T and S. The coefficient of transmissibility is then computed by the formula

$$T = [114.6\ q\ W(u)/s]$$

and the coefficient of storage is computed by the formula

$$S = (uTt/1.87r^2)$$

This method is applicable when the draw-downs are caused by one discharging well, and has been used successfully by the writers [4] and others [3,5]. Where the draw-downs are caused by the discharge of two or more wells, however, the graphical method cannot be used precisely in the manner just described and special type-curves must be constructed for each test.

Multiple well-systems

The draw-down at any point on the cone of depression caused by the discharge of several wells is equal to the sum of the draw-downs caused by the discharge of each well. Thus

$$s_t = s_A + s_B + s_C + \ldots\ldots s_N$$

where s_t is the total draw-down, and s_A, s_B, s_C, ... and s_N are the draw-downs caused, respectively, by the discharge of wells A, B, C, ... and N. Thus

$$s_t = (114.6/T)\,[q_A W(u_A) + q_B W(u_B) + q_C W(u_C) + \ldots . q_N W(u_N)]$$

and

$$u_A = (1.87\, r_A^2\, S/Tt_A) \qquad u_B = (1.87\, r_B^2\, S/Tt_B)$$

$$u_C = (1.87\, r_C^2\, S/Tt_C) \qquad u_N = (1.87\, r_N^2\, S/Tt_N)$$

where r_A, r_B, r_C, and r_N are the distances, respectively, from the discharging wells to the point of observation, and t_A, t_B, t_C, and t_N are the periods, respectively, that the discharging wells have been operated. For any particular test, u_B, u_C, ... and u_N can be expressed in terms of u_A, as follows:

$$u_B = [(r_B^2\ t_A/r_A^2\ t_B)\ u_A] \qquad u_C = [(r_C^2\ t_A/r_A^2\ t_C)\ u_A] \quad \ldots . .$$

$$u_N = [(r_N^2\ t_A/r_A^2\ t_N)\ u_A]$$

As a result, a special type-curve can be prepared for any time and any point on the cone of depression in the following manner: (1) Assume a value for u_A; (2) compute therefrom the related values of u_B, u_C, ... u_N; (3) determine from a table of the integral the values of $W(u_A)$, $W(u_B)$, $W(u_C)$, ... $W(u_N)$; (4) correct these values for differences in rate of discharge of wells A, B, C, ... N by multiplying $W(u_A)$ by the ratio (q_A/q_m)--where q_m is the discharge, in gallons a minute, of the well with the smallest yield--$W(u_B)$ by the ratio (q_B/q_m), etc.; (5) plot on logarithmic paper the sum of the corrected values of $W(u_A)$, $W(u_B)$, $W(u_C)$, ... $W(u_N)$--that is $\Sigma\, W(u)$--against the sum of the values of u_A, u_B, u_C, ... u_N--that is, Σu; (6) repeat the process by progressively assuming other values for u_A until sufficient points have been plotted to define the special type-curve.

When T and S are to be determined from the draw-downs in one well, a special type-curve is computed in the manner just described for each available measurement of draw-down, and all these curves are plotted on one sheet of logarithmic paper. The draw-downs are then plotted on another sheet of logarithmic paper (to the same scale as used for plotting the special type-curve) against corresponding values of $\Sigma(r^2/t)$. The plotted points are fitted over the sheet of special type-curves (keeping the axes of the paper aligned) until each point falls on its corresponding type-curve. The ordinates and abscissas for one of the points are read off the appropriate special type-curve, and T and S are computed by the following equations

$$T = (114.6\, q_m/s)\ \ \Sigma W(u)$$

$$S = T\ \ \Sigma u/[1.87\ \ \Sigma (r^2/t)]$$

When T and S are to be determined from the draw-downs at any time in a line of observation-wells, a special type-curve is computed for each well by the same process. The draw-downs in the several observation-wells are then plotted on another sheet of logarithmic paper (to the same scale as used for plotting the special type-curves) against corresponding values of $\Sigma(r^2/t)$. The points are fitted over the special type-curves (keeping the axes of the paper aligned) until each point falls on its corresponding special type-curve. The ordinate and the abscissa for one of the points are read off the special type-curve and T and S are computed from the equations given above.

Example of method

The process can be illustrated by an example in which the following assumptions are made: There are two discharging wells, A and B, and three observation-wells, 1, 2, and 3, situated as shown in Figure 1. Well A discharges 750 gallons a minute and Well B discharges 250 gallons a minute; the discharge of Well B begins one day later than the discharge of Well A. The transmissibility- and storage-coefficients of the formation are, respectively, 100,000 and 0.10. On these assumptions the resulting draw-downs of the water-levels in observation-wells 1 to 3 can be computed by the non-equilibrium formula for any time (see Table 1). Computed draw-down

Table 1--Draw-down, in feet, of the water-levels in observation-wells, resulting from the discharge of wells A and B

Well No.	t_A	u_A	$W(u_A)$	u_B	$W(u_B)$	s_A	s_B	s_t
1	1.167	.0361	2.78	.0280	3.03	2.39	0.87	3.26
1	1.500	.0281	3.02	.0093	4.11	2.59	1.18	3.77
1	2.000	.0210	3.30	.0047	4.79	2.84	1.37	4.21
2	1.167	.1000	1.82	.252	1.04	1.56	0.30	1.86
2	1.500	.0780	2.05	.0842	1.98	1.76	0.57	2.33
2	2.000	.0584	2.32	.0421	2.63	1.99	0.75	2.74
3	1.167	.0965	1.24	.700	0.37	1.07	0.11	1.18
3	1.500	.1525	1.45	.234	1.10	1.25	0.315	1.56
3	2.000	.1145	1.70	.117	1.68	1.46	0.48	1.94

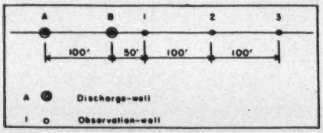

Fig. 1--Location of wells assumed for example of method

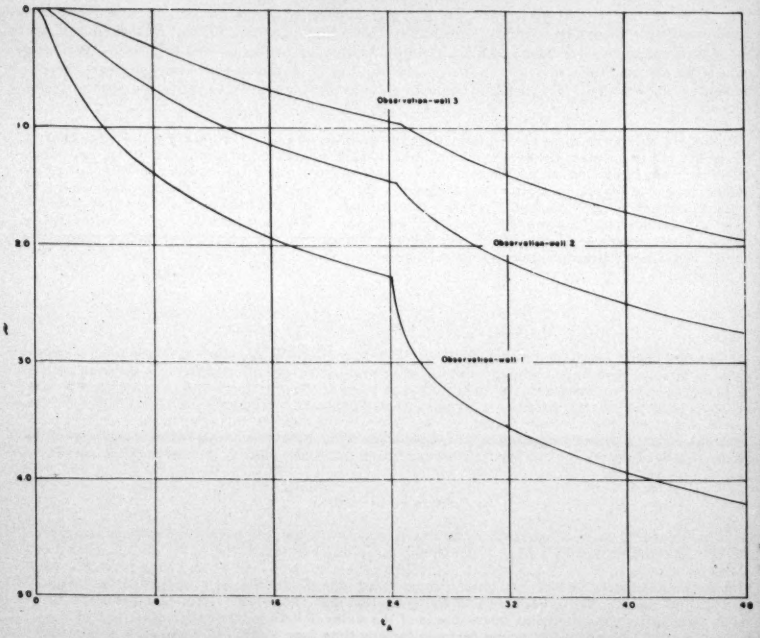

Fig. 2--Draw-down curves for observation-wells in assumed example of method

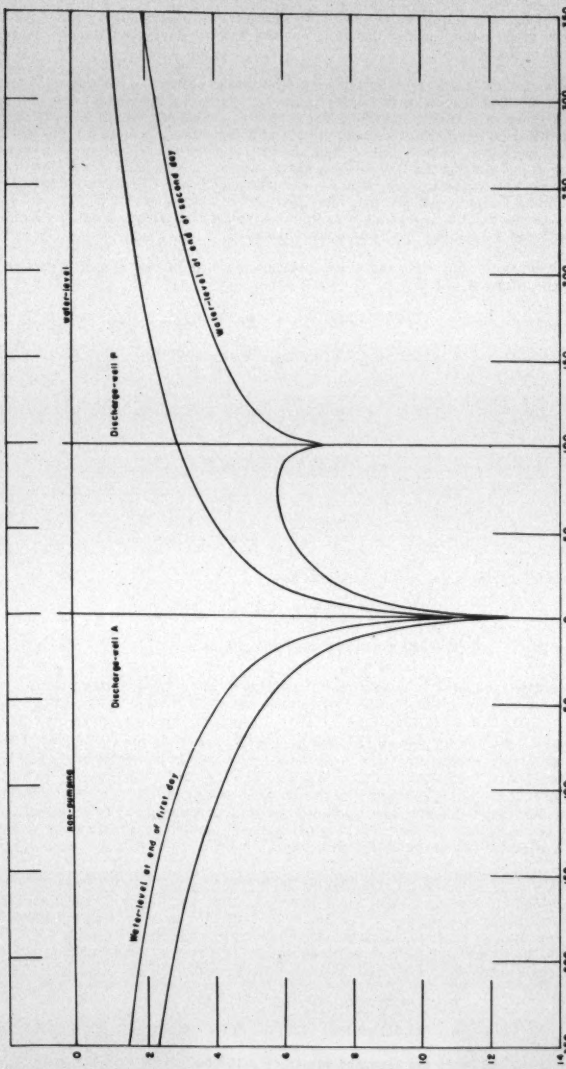

Fig. 3--Profiles of the cone of depression in assumed example of method

curves for the three observation-wells are shown in Figure 2 and computed profiles of the cone of depression taken along a line through the wells one day and two days after the discharge of Well A began are shown in Figure 3.

Assume now that the coefficients of transmissibility and storage in the above-described locality are unknown, and that it is desired to determine them from a discharging-well test made according to the procedure just outlined (Well A operated at a constant rate of 750 gallons a minute for two days and Well B operated at a constant rate of 250 gallons a minute for the last day). The coefficients can, of course, be determined from the draw-downs in one observation-well or from the draw-downs at one time in the line of observation-wells. Let us first utilize the draw-downs in one observation-well--for example, Well 2. According to Table 1, the draw-downs in Well 2 are 1.86, 2.33, and 2.74 feet, respectively, after Well A had been operated 28, 36, and 48 hours. We may now construct special type-curves to fit the physical conditions of the test and solve graphically for T and S, utilizing the draw-downs in Well 2.

The draw-down, s_t, at any time and at any point on the cone of depression resulting from the discharge of wells A and B will be

$$s_t = (114.6/T)\,[q_A\,W(u_A) + q_B\,W(u_B)]$$

$$s_t = (114.6\,q_B/T)\,[(q_A/q_B)\,W(u_A) + W(u_B)]$$

and

$$u_A = (1.87\,r_A^2\,S/Tt_A)$$

$$u_B = (1.87\,r_B^2\,S/Tt_B)$$

whence

$$u_B = (r_B^2\,t_A/r_A^2\,t_B)u_A$$

Substituting known factors in the above equation for s_t

$$s_t = [(114.6)\,(250)/(T)]\,[3\,W(u_A) + W(u_B)]$$

$$s_t = (28{,}650/T)\,[3\,W(u_A) + W(u_B)]$$

First, a special type-curve is constructed for 28 hours after the discharge of Well A began. Assume a value for u_A--for example, 0.06--and compute u_B. Since $u_B = (r_B^2\,t_A/r_A^2\,t_B)\,(u_A)$, $u_B = [(22{,}500)\,(1.167)/(62{,}500)\,(0.167)]\,0.06 = 0.151$. From a table of the exponential integral for $u_A = 0.06$, $W(u_A) = 2.30$, and for $u_B = 0.151$, $W(u_B) = 1.46$. These values of W(u) are corrected, the difference in discharge of wells A and B by multiplying each by the ratio of $(q_N/q_m) = (q_N/q_B) = (q_N/250)$. Thus $\Sigma W(u) = (q_A/250)\,(2.30) + (q_B/250)\,(1.46) = (3)\,(2.30) + 1.46 = 8.36$. This point, $\Sigma W(u) = 8.36$ and $\Sigma u = 0.211$, is plotted on logarithmic paper (see Fig. 4). Additional points on the special type-curve are obtained by assuming other values for u_A (see Table 2), until sufficient values are obtained to define the curve. The whole process is then repeated for the draw-downs 36 and 48 hours after the discharge of Well A began.

The draw-downs in Well 2 at the three times are plotted against $\Sigma(r^2/t)$ (see Table 3) on another sheet of logarithmic paper (Fig. 5). Figure 5 is fitted over Figure 4 until each point falls on its corresponding special-type curve, and the coordinates for one of the matched points are read from the appropriate curve. This process was followed and for the point $s_t = 2.33$ and $\Sigma(r^2/t) = 86{,}667$, the following values were obtained from the special type-curve for 36 hours: $\Sigma[W(u)] = 8.10$ and $\Sigma u = 0.165$. Then

$$T = (114.6)(250)(8.10)/2.33 = 99{,}611$$

$$S = (99{,}611)(0.165)/[1.87\,(86{,}667)] = 0.1014$$

The discrepancies between the assumed values (T = 100,000 and S = 0.10) result chiefly from unavoidable inaccuracies of plotting and matching of the points and curves.

Table 2--Data for plotting special-type curves for observation-well 2

u_A	u_B	$W(u_A)$	$W(u_B)$	$q_A W(u_A)/q_B$	$\Sigma u = (u_A + u_B)$	$\Sigma W(u) = q_A W(u_A)/q_B + W(u_B)$
			1.167 days (28 hours); $(r_B^2 t_A / r_A^2 t_B) = 2.52$			
.06	.151	2.30	1.46	6.90	0.211	8.36
.07	.176	2.15	1.33	6.45	.246	7.78
.08	.202	2.03	1.21	6.09	.282	7.73
.09	.227	1.92	1.12	5.76	.317	6.88
.10	.252	1.82	1.04	5.46	.352	6.50
.11	.277	1.74	0.97	5.22	.387	6.19
.12	.302	1.66	0.90	4.98	.422	5.88
.13	.328	1.59	0.84	4.77	.458	5.61
			1.5 days (36 hours); $(r_B^2 t_A / r_A^2 t_B) = 1.08$			
.04	.0432	2.68	2.61	8.04	0.0832	10.65
.05	.0540	2.47	2.40	7.41	.1040	9.81
.06	.0648	2.30	2.22	6.90	.1248	9.12
.07	.0756	2.15	2.08	6.45	.1456	8.53
.08	.0864	2.03	1.96	6.09	.1664	8.05
.09	.0972	1.92	1.85	5.76	.1872	7.61
.10	.1080	1.82	1.75	5.46	.2080	7.21
.11	.1188	1.74	1.67	5.22	.2288	6.89
.12	.1296	1.66	1.59	4.98	.2496	6.57
			2 days (48 hours); $(r_B^2 t_A / r_A^2 t_B) = 0.72$			
.02	.0144	3.35	3.68	10.05	0.0344	13.73
.03	.0216	2.96	3.28	8.88	.0516	12.16
.04	.0288	2.68	3.00	8.04	.0688	11.04
.05	.0360	2.47	2.78	7.41	.0860	10.19
.06	.0432	2.30	2.61	6.90	.1032	9.51
.07	.0504	2.15	2.46	6.45	.1204	8.91
.08	.0576	2.03	2.33	6.09	.1376	8.42
.09	.0648	1.92	2.22	5.76	.1548	7.98

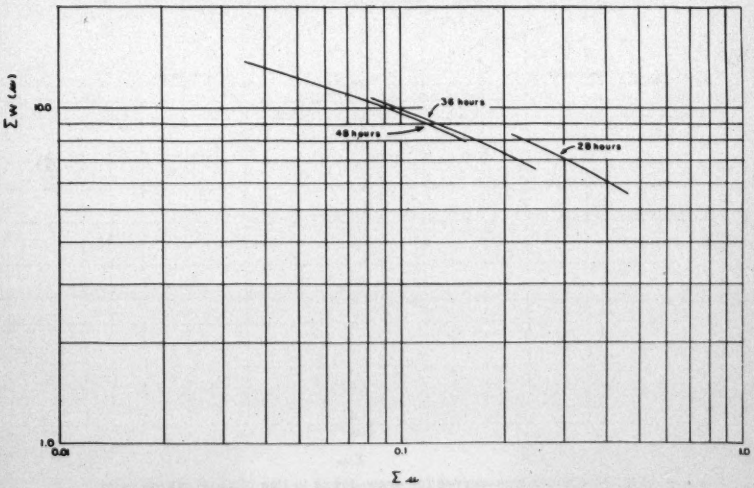

Fig. 4--Special type-curves for draw-downs in observation-well 2

Table 3--Data for plotting s_t against $\Sigma(r^2/t)$ for observation-well 2

t_A	t_B	r_A^2	r_B^2	(r_A^2/t_A)	(r_B^2/t_B)	$\Sigma(r^2/t)$	s_t
1.167	0.167	62,500	22,500	53,571	135,000	188,571	1.86
1.500	0.500	62,500	22,500	41,667	45,000	86,667	2.33
2.000	1.000	62,500	22,500	31,250	22,500	53,750	2.74

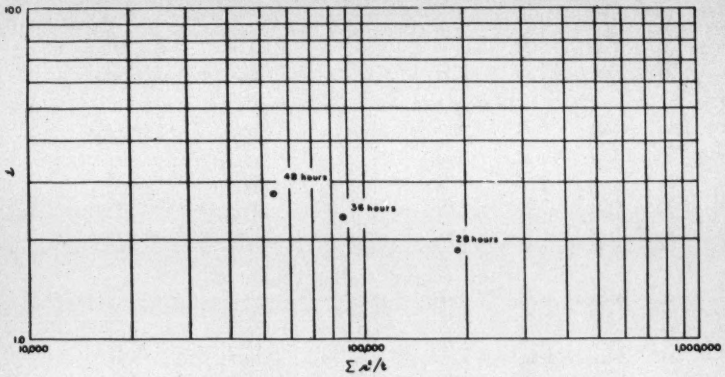

Fig. 5--Points corresponding to draw-downs in observation-well 2

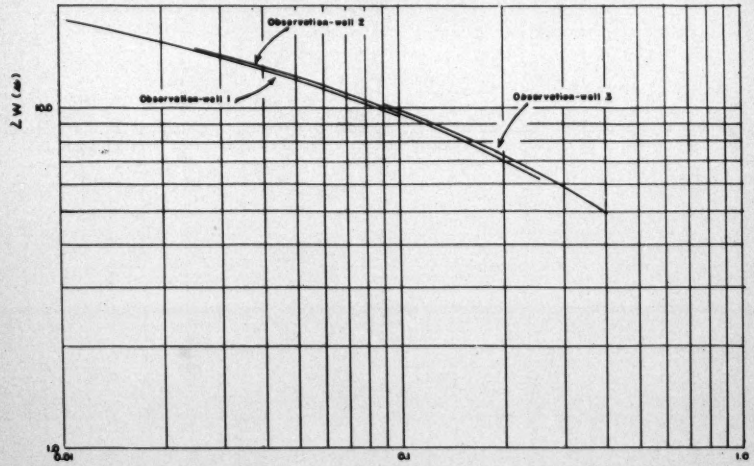

Fig. 6--Special type-curves for draw-downs in line of observation-wells

Table 4--Data for plotting special-type curves of line of observation-wells

Obs.-well No.	u_A	u_B	$W(u_A)$	$W(u_B)$	$(q_A/q_B)W(u_A)$	$(u_A + u_B)$	$(q_A/q_B)W(u_A) + W(u_B)$
1	$r_A = 150$; $r_B = 50$; $(r_B^2 t_A)/(r_A^2 t_B) = 0.222$						
	.010	.0022	4.03	5.53	12.09	0.0122	17.62
	.012	.0027	3.86	5.34	11.58	0.0147	16.92
	.015	.0033	3.64	5.13	10.92	0.0183	16.05
	.018	.0040	3.46	4.95	10.38	0.0220	15.33
	.021	.0047	3.31	4.80	9.93	0.0257	14.73
	.025	.0056	3.14	4.63	9.42	0.0306	14.05
	.030	.0067	2.96	4.44	8.88	0.0367	13.32
	.038	.0084	2.73	4.21	8.19	0.0464	12.40
	.050	.0111	2.47	3.93	7.41	0.0611	11.34
	.065	.0144	2.22	3.69	6.66	0.0794	10.35
	.080	.0178	2.03	3.47	6.09	0.0978	9.56
2	$r_A = 250$; $r_B = 150$; $(r_B^2 t_A)/(r_A^2 t_B) = 0.72$						
	.015	.0108	3.64	3.96	10.92	0.0258	14.88
	.020	.0144	3.35	3.68	10.05	0.0344	13.73
	.028	.0202	3.03	3.34	9.09	0.0482	12.43
	.040	.0288	2.68	3.00	8.04	0.0688	11.04
	.060	.0432	2.30	2.61	6.90	0.1032	9.51
	.080	.0576	2.03	2.33	6.09	0.1376	8.42
	.100	.0720	1.82	2.12	5.46	0.1720	7.58
	.120	.0864	1.66	1.96	4.98	0.2064	6.94
	.140	.1008	1.52	1.82	4.56	0.2408	6.38
3	$r_A = 350$; $r_B = 250$; $(r_B^2 t_A)/(r_A^2 t_B) = 1.02$						
	.050	.051	2.47	2.45	7.41	0.101	9.86
	.065	.066	2.22	2.20	6.66	0.131	8.86
	.085	.087	1.97	1.95	5.91	0.172	7.86
	.100	.102	1.82	1.80	5.46	0.202	7.26
	.120	.122	1.66	1.64	4.98	0.242	6.62
	.150	.153	1.46	1.45	4.38	0.303	5.83
	.200	.204	1.22	1.21	3.66	0.404	4.87

Let us now determine T and S from the draw-downs in the line of observation-wells at some time--for example, 48 hours after the discharge of Well A began. A special-type curve is constructed for each well in the usual manner (see Table 4 and Fig. 6) and the draw-downs in the three wells 48 hours after the discharge of Well A began are plotted against $\Sigma(r^2/t)$ on another sheet of logarithmic paper (see Table 5 and Fig. 7). Figure 7 is fitted over Figure 6 until each point falls on its corresponding special-type curve and the coordinates for one of the matched points are read from the appropriate curve. This process was followed and, for the point s_t = 1.94 and $\Sigma(r^2/t) = 123{,}750$, the following values were obtained from the special-type curve for observation-well 3: $\Sigma[W(u)] = 6.75$, $\Sigma u = 0.234$. Then

$$T = (114.6)(250)(6.75)/1.94 = 99{,}684$$

$$S = (99{,}684)(0.234)/[1.87\,(123{,}750)] = 0.1008$$

which compare favorably with the assumed values.

Table 5--Data for plotting s_t against $\Sigma(r^2/t)$ for line of observation-wells

Obs.-well No.	r_A	r_B	r_A^2	r_B^2	(r_A^2/t_A)	(r_B^2/t_B)	$\Sigma(r^2/t)$	s_t
1	150	50	22,500	2,500	11,250	2,500	13,750	4.21
2	250	150	62,500	22,500	31,250	22,500	53,750	2.74
3	350	250	122,500	62,500	61,250	62,500	123,750	1.94

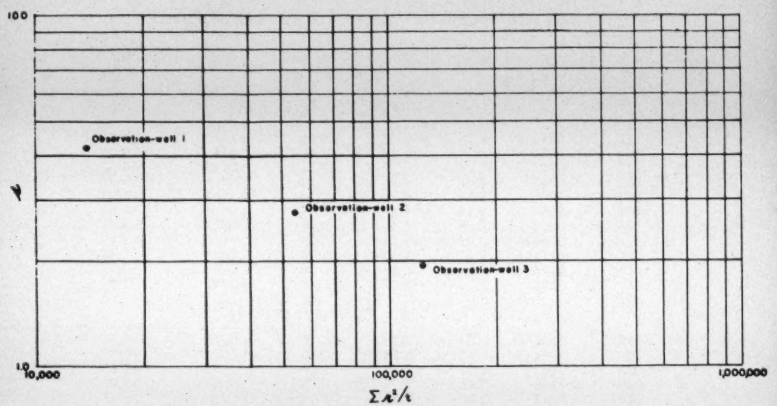

Fig. 7--Points corresponding to draw-downs in line of observation-wells

The method just described is theoretically applicable to any test. Heterogeneity of the water-bearing formation, and other differences between assumed and actual conditions may, however, introduce serious errors, and it behooves the investigator to measure draw-downs at as many points as possible on the cone of depression, and to utilize all these points in attempting to arrive at the most nearly correct result.

Application of method to pumping test near Oakes, North Dakota

A pumping test that involved a multiple well-system was made at Oakes, North Dakota, in September, 1940, for the purpose of determining the coefficients of transmissibility and storage of the sand and silt that form the bed of glacial Lake Dakota. The work was done in connection with a detailed investigation of the geology and ground-water resources of the area made by the Geological Survey, United States Department of the Interior, in cooperation with the North Dakota Geological Survey.

Six wells, each three inches in diameter and about 25 feet deep, were pumped simultaneously at a combined rate of about 260 gallons a minute for 16 hours and 50 minutes. The wells were situated on a line about eight feet apart. Four observation-wells were constructed on the same line at the locations indicated in Figure 8, and measurements of the water-levels in them were made regularly during the period of pumping and for about 33 hours after pumping stopped. The water-levels in the pumped wells could not be measured. The thickness of lake sand and silt at Oakes is estimated from nearby test-holes to be about 60 feet, and the non-pumping water-table at the time of the test stood about 12 feet below the land-surface. The saturated thickness of water-bearing material was thus about 48 feet.

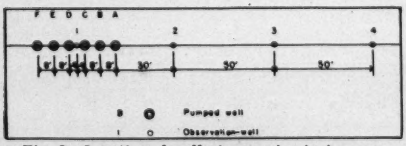

Fig. 8--Location of wells in pumping tests near Oakes, North Dakota

The measured draw-downs in the observation-wells at the end of the period of pumping (0.7 day) were as follows: 2.65 feet in Well 1; 1.60 feet in Well 2; 0.95 foot in Well 3; and 0.59 foot in Well 4. The draw-down in Well 1 was not used in determining transmissibility- and storage-coefficients because it is believed to have been unduly influenced by irregularities in the rate of pumping and by differences in the individual yields of the pumped wells. The recovery of the water-level in Well 1 after pumping stopped was utilized, how-

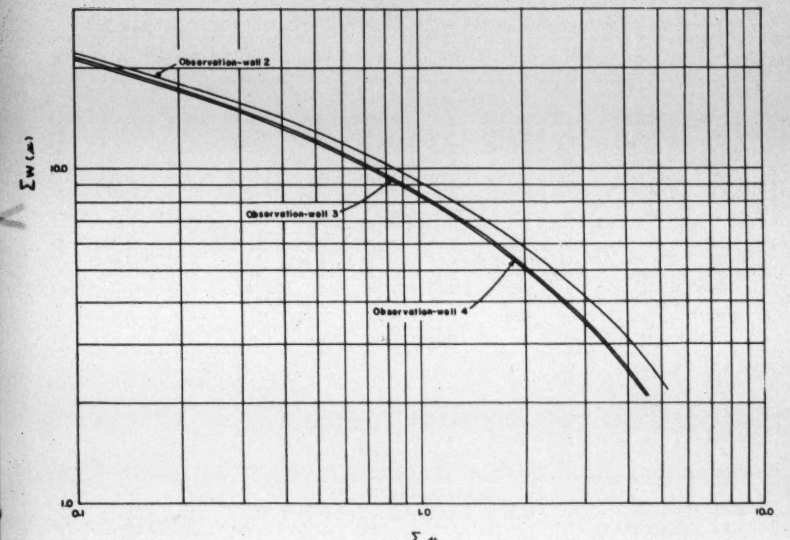

Fig. 9--Special type-curves for draw-downs in line of wells at Oakes, North Dakota

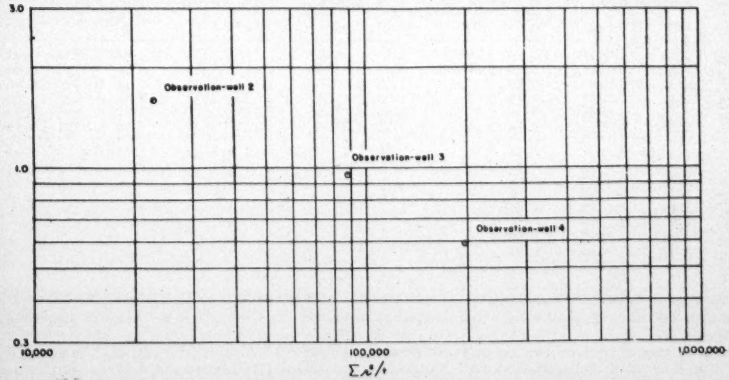

Fig. 10--Points corresponding to draw-downs in line of wells at Oakes, North Dakota

ever, to determine the coefficient of transmissibility by the recovery-method [see 1 of "References" at end of paper].

Using the procedure outlined earlier in this paper for a line of observation-wells, special type-curves were constructed on logarithmic paper for observation-wells 2, 3, and 4 (see Table 6

Table 6--Data for plotting special-type curves for line of observation-wells in Oakes test

u_N	$(r_B^2 r_A^2)$	u	W(u)	u	W(u)	u	W(u)	u	W(u)	u	W(u)
					Observation-well 2						
u_A	1.000	0.002233	5.53	0.004188	4.90	0.005583	4.62	0.008375	4.21	0.01396	3.71
u_B	1.604	0.003582	5.06	0.006718	4.43	0.008955	4.15	0.01343	3.75	0.02239	3.24
u_C	2.351	0.005251	4.68	0.009846	4.05	0.01313	3.77	0.01969	3.37	0.03282	2.87
u_D	3.240	0.007236	4.36	0.01357	3.74	0.01809	3.45	0.02714	3.06	0.04523	2.56
u_E	4.271	0.009539	4.08	0.01789	3.46	0.02385	3.18	0.03577	2.79	0.05962	2.30
u_F	5.444	0.01216	3.85	0.02280	3.23	0.03039	2.95	0.04559	2.56	0.07600	2.07
Σ	.....	0.040	27.56	0.075	23.81	0.10	22.12	0.15	19.74	0.25	16.68
u_A	1.000	0.02233	3.25	0.04188	2.64	0.05583	2.36	0.08375	1.98	0.1396	1.53
u_B	1.604	0.03582	2.79	0.06718	2.19	0.08955	1.92	0.1343	1.56	0.2239	1.13
u_C	2.351	0.05251	2.42	0.09846	1.84	0.1313	1.58	0.1969	1.24	0.3282	0.84
u_D	3.240	0.07236	2.12	0.1357	1.55	0.1809	1.31	0.2714	0.98	0.4523	0.62
u_E	4.271	0.09539	1.87	0.1789	1.32	0.2385	1.08	0.3577	0.78	0.5962	0.46
u_F	5.444	0.1216	1.65	0.2280	1.12	0.3039	0.90	0.4559	0.62	0.7600	0.33
Σ	.....	0.40	14.10	0.75	10.66	1.0	9.15	1.5	7.16	2.5	4.91
u_A	1.000	0.2233	1.13								
u_B	1.604	0.3582	0.78								
u_C	2.351	0.5251	0.53								
u_D	3.240	0.7236	0.36								
u_E	4.271	0.9539	0.24								
u_F	5.444	1.216	0.15								
Σ	.....	4.0	3.19	.....	.....	.....	.....	.....	.....	.....	.....
					Observation-well 3						
u_A	1.00	0.004189	4.90	0.007853	4.28	0.01047	3.99	0.01571	3.59	0.02618	3.09
u_B	1.21	0.005068	4.71	0.009502	4.09	0.01267	3.80	0.01901	3.40	0.03168	2.91
u_C	1.44	0.006031	4.54	0.01131	3.92	0.01508	3.63	0.02262	3.23	0.03770	2.74
u_D	1.69	0.007079	4.38	0.01327	3.76	0.01770	3.47	0.02655	3.08	0.04424	2.58
u_E	1.96	0.008210	4.23	0.01539	3.61	0.02052	3.33	0.03079	2.93	0.05131	2.44
u_F	2.25	0.009424	4.10	0.01767	3.48	0.02356	3.19	0.03535	2.80	0.05891	2.32
Σ	.....	0.040	26.86	0.075	23.14	0.10	21.41	0.15	19.03	0.25	16.08
u_A	1.00	0.04189	2.64	0.07853	2.04	0.1047	1.78	0.1571	1.42	0.2618	1.01
u_B	1.21	0.05068	2.46	0.09502	1.87	0.1267	1.61	0.1901	1.26	0.3168	0.87
u_C	1.44	0.06031	2.29	0.1131	1.71	0.1508	1.46	0.2262	1.12	0.3770	0.74
u_D	1.69	0.07079	2.14	0.1327	1.57	0.1770	1.32	0.2655	1.00	0.4424	0.64
u_E	1.96	0.08210	2.00	0.1539	1.44	0.2052	1.20	0.3079	0.89	0.5131	0.54
u_F	2.25	0.09424	1.88	0.1767	1.33	0.2356	1.09	0.3535	0.79	0.5891	0.46
Σ	.....	0.40	13.41	0.75	9.96	1.0	8.46	1.5	6.48	2.5	4.26
u_A	1.00	0.4189	0.67								
u_B	1.21	0.5068	0.55								
u_C	1.44	0.6031	0.45								
u_D	1.69	0.7079	0.37								
u_E	1.96	0.8210	0.30								
u_F	2.25	0.9424	0.24								
Σ	.....	4.0	2.58	.....	.....	.....	.....	.....	.....	.....	.....

and Fig. 9), and values of s were plotted against values of $\Sigma(r^2/t)$ on another sheet of logarithmic paper of the same scale (see Table 7 and Fig. 10). The sheet of plotted points was placed over the sheet of special type-curves and adjusted (keeping the axes of the paper aligned) until each point fell on its corresponding type-curve. Values for $\Sigma W(u)$ and Σu for each of the three points were then read off the appropriate curves. The observed values for Well 2 were $\Sigma W(u) = 20.35$ and $\Sigma u = 0.134$ or which $s_t = 1.60$ and $\Sigma(r^2/t) = 23{,}029$. The coefficient of transmissibility is thus computed to be $T = (114.6)(43.3)(20.35/1.60) = 63{,}119$ and the coefficient of storage is $S = (63{,}119)(0.134)/(1.87)(23{,}029) = 0.196$.

Values from the curve for Well 3 were $\Sigma W(u) = 12.1$ and $\Sigma u = 0.505$, for which $s_t = 0.95$ and $\Sigma(r^2/t) = 87{,}314$. $T = (114.6)(43.3)(12.1)/0.95 = 63{,}218$ and $S = (63{,}218)(.505)/(1.87)(87{,}314) = 0.196$.

Table 6--Data for plotting special-type curves for line of observation-wells in Oakes test--Concluded

u_N	$(r_B^2 r_A^2)$	u	W(u)	u	W(u)	u	W(u)	u	W(u)	u	W(u)
					Observation-well 4						
u_A	1.000	0.004966	4.73	0.009311	4.11	0.01242	3.82	0.01862	3.42	0.03104	2.93
u_B	1.127	0.005597	4.62	0.01049	3.99	0.01400	3.71	0.02099	3.31	0.03498	2.81
u_C	1.261	0.006262	4.50	0.01174	3.88	0.01566	3.60	0.02348	3.20	0.03914	2.70
u_D	1.403	0.006967	4.40	0.01306	3.77	0.01743	3.50	0.02612	3.09	0.04355	2.60
u_E	1.553	0.007712	4.29	0.01446	3.67	0.01929	3.39	0.02892	3.00	0.04821	2.50
u_F	1.710	0.008492	4.20	0.01592	3.58	0.02124	3.30	0.03184	2.90	0.05308	2.41
Σ	.....	0.040	26.74	0.075	23.00	0.10	21.32	0.15	18.92	0.25	15.95
u_A	1.000	0.04966	2.47	0.09311	1.89	0.1242	1.63	0.1862	1.28	0.3104	0.88
u_B	1.127	0.05597	2.36	0.1049	1.78	0.1400	1.52	0.2099	1.19	0.3498	0.79
u_C	1.261	0.06262	2.26	0.1174	1.68	0.1566	1.43	0.2348	1.09	0.3914	0.72
u_D	1.403	0.06967	2.15	0.1306	1.58	0.1743	1.34	0.2612	1.01	0.4355	0.65
u_E	1.553	0.07712	2.06	0.1446	1.50	0.1929	1.25	0.2892	0.93	0.4821	0.58
u_F	1.710	0.08492	1.97	0.1592	1.41	0.2124	1.17	0.3184	0.86	0.5308	0.52
Σ	.....	0.40	13.27	0.75	9.84	1.0	8.34	1.5	6.36	2.5	4.14
u_A	1.000	0.4966	0.56								
u_B	1.127	0.5597	0.49								
u_C	1.261	0.6262	0.43								
u_D	1.403	0.6967	0.38								
u_E	1.553	0.7712	0.33								
u_F	1.710	0.8492	0.29								
Σ	.....	4.0	2.48	.....	.....	.....	.....	.....	.....	.....	.....

Table 7--Data for plotting s_t against $\Sigma(r^2/t)$ for line of observation-wells in Oakes test (t = 0.7)

Obs.-well	r_A^2	r_B^2	r_C^2	r_D^2	r_E^2	r_F^2	$\Sigma(r^2)$	$\Sigma(r^2/t)$	s
2	900	1,444	2,116	2,916	3,844	4,900	16,120	23,029	1.60
3	6,400	7,744	9,216	10,816	12,544	14,400	61,120	87,314	0.95
4	16,900	19,044	21,316	23,716	26,244	28,900	136,120	194,457	0.59

Values for Well 4 were $\Sigma W(u) = 7.5$ and $\Sigma u = 1.14$, for which $s_t = 0.59$ and $\Sigma r^2/t = 194,457$. $T = (114.6)(43.3)(7.5)/0.59 = 63,069$ and $S = (63,069)(1.14)/(1.87)(194,457) = 0.198$.

The average of the several determinations gives T = 63,135 and S = 0.197.

The average value for the transmissibility-coefficient just obtained can be roughly checked by applying to the data collected during the test an adaptation of the equilibrium-formula [4], and also by utilizing the recovery-formula developed by THEIS [1].

The equilibrium-formula can be adapted approximately to this test by writing it as follows

$$T = [527.7\ q/(s_1 - s_2)]\ [\log_{10}(r_{2A}\ r_{2B}\ r_{2C} \cdots / r_{1A}\ r_{1B}\ r_{1C} \cdots)]$$

in which q is the discharge (in gallons a minute) of one of the pumped wells, s_1 is the draw-down (in feet) in a near observation-well, s_2 is the draw-down (in feet) in a far observation-well, r_{1A}, r_{1B}, r_{1C}, etc., are the respective distances (in feet) from the near observation-well to pumped wells A, B, C, etc., and r_{2A}, r_{2B}, r_{2C}, etc., are the respective distances (in feet) from the far observation-well to the pumped wells.

Values of $\log_{10}(r_{2A}\ r_{2B}\ r_{2C} \cdots / r_{1A}\ r_{1B}\ r_{1C} \cdots)$ for the three possible combinations of two observation-wells were plotted against corresponding values of $(s_1 - s_2)$ on ordinary graph

paper and a straight line was drawn as nearly as possible through the points and through the origin. The slope of this line was 2.95. Thus T = (527.7) (43.3) (2.95) = 67,405.

The fact that the transmissibility-coefficient determined by this method is somewhat higher than that computed by the method of multiple well-systems is caused chiefly by failure of the cone of depression to reach an essential equilibrium-form in the comparatively short period of pumping.

The recovery-formula [1] may be written for the Oakes test

$$T = [(264\ q/s_1)]\ [\log_{10}\ (t/t^1)]$$

in which q is the combined rate of pumping of the wells (in gallons a minute), s_1 is the residual draw-down of the water-level in the observation-well 1 at time t^1 (in days) after pumping stopped, and t is the time (in days) after pumping began. Values of $\log_{10}\ (t/t^1)$ were plotted against corresponding values of s_1 on ordinary graph paper and a straight line was drawn as nearly as possible through the plotted points. The slope of this line was 0.94. Thus T = (264) (260) (0.94) = 64,522, which compares favorably with the values obtained by the method involving multiple well-systems.

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DISCUSSION

M. KING HUBBERT (Office of Economic Warfare, Washington, D. C.)--One of the more important developments in the study of discharging wells made during recent years resulted when C. V. THEIS, in 1935, adapted the equations for the non-steady conduction of heat from a line-source to the analogous problem of the flow of ground-water into a well. In 1940, C. E. JACOB developed the same equations directly from hydrologic factors without recourse to heat-conduction analogies. The present paper is devoted to extending the work of Theis and Jacob, by means of the principle of superposition, to the case where a number of observation-wells are affected simultaneously by multiple discharging-wells.

The paper describes lucidly the application of a graphical method for the determination of the coefficients of transmissibility and storage of the aquifer when only one well is discharging, and then generalizes this to the discharge of a multiple system of wells, illustrating the method with a special case of two discharging wells and three observation-wells. The weakness of the paper lies in its almost complete failure to justify the operations described.

The graphical method applicable to a single discharging-well is credited to Theis by a "personal communication". Jacob also employed the method, and likewise attributed it to Theis. Since this method is fundamental to the present paper and its justification has not been given, a simple but not necessarily obvious development of it is offered below.

Neglecting numerical coefficients resulting from the unnecessary employment of inconsistent units of measurement, the equations for the draw-down of the piezometric surface due to a single discharging-well are (1) and (2).

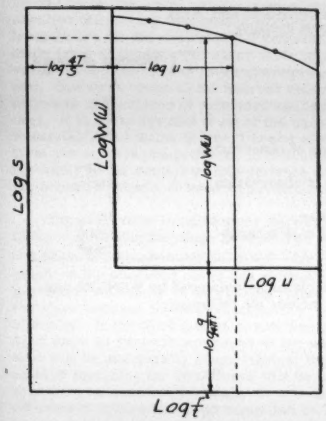

Fig. 1--Relation between log u and log W(u) and log s and log (r^2/t)

$$s = (q/4\pi T)\, W(u) \quad (1)$$

$$u = (S/4T)\,(r^2/t) \quad (2)$$

where the meaning of the symbols is the same as in the paper under discussion. The draw-down s, the time t, distance r, and discharge q are all directly observable quantities. The coefficient of storage S and of transmissibility T are the unknowns to be determined.

If we rewrite equations (1) and (2) so as to separate the knowns from the unknowns and take the logarithms of both sides we obtain equations (3) and (4).

$$\log s = \log (q/4\pi T) + \log W(u) \quad (3)$$

$$\log (r^2/t) = \log (4T/S) + \log u \quad (4)$$

Since q, T, and S are constants, it is clear that if we plot log W(u) as a function of log u, and then superpose upon this observed pairs of values of log s as a function of log (r^2/t), plotted to the same scale, so that the observed points lie upon the curve log u against log W(u), the two sets of axes will differ by the displacements log (4T/S) and log $(q/4\pi T)$. From these displacements the values of S and T can be determined. This is illustrated by Figure 1.

The authors describe an extension of this graphical solution to any number of pumping wells, and give a numerical example of the application of the method for the special case of two pumping wells A and B, and three observation-wells, 1, 2, and 3. The physical basis for the extension is the principle of superposition whereby it is assumed that the total draw-down at a given observation-well produced by several pumping wells is the algebraic sum of the draw-downs that would be produced by each pumping well separately.

This assumption is apparently justified so that the procedure of generalization is one of proper algebraic summation of the separate effects. An algebraic analysis of a physical problem consists, in effect, of the performance of a model-experiment with the physical elements of the problem, each of which is given a token representation by means of a distinctive symbol. The operations allowable with the tokens must be in accord with those imposed by the physical relations in the original. If, in the algebraic operation, any of the essential elements of the problem are omitted, or if different elements are insufficiently identified (for example, by the use of the same symbol for different elements), or, finally, if the operations performed upon the tokens are not in accordance with the physical requirements of the original, error or unintelligibility will result.

In the multiple-well problem, the number of essential physical quantities which must be uniquely identified is large. These quantities include: (1) The pumping wells; (2) the observation-wells; (3) the times of observation; (4) the radial distances from each pumping well to each observation-well; (5) the partial draw-downs at each observation-well and time of observation, due to each pumping well; (6) the total draw-downs at each observation-well and time of observation; (7) the discharge of each pumping well; (8) the duration of pumping of each discharging well at each time of observation; (9) the function u(r,t) for each radial distance and duration of discharge; and (10) the function W(u) for each value of u.

An idea of the ensemble of elements to be considered can be obtained from Table 1. If n is taken as the number of pumping wells, m the number of observation-wells, and ℓ that of the times of observation (assumed the same for all observation-wells), the number of each of the remaining quantities can be derived in terms of these three. For example: The number of radial distances from pumping wells to observation-wells will be mn; the number of partial draw-downs will be ℓmn; and so for the remaining quantities. Furthermore, each of these elements must be explicitly recognized and uniquely identified by a distinctive algebraic symbol.

Table 1--Types and numbers of physical quantities that must be considered in the multiple-well problem

No.	Type of physical quantity	Number of items
1	Pumping well	n
2	Observation-well	m
3	Time of observation	ℓ
4	Distance from pumping well to observation-well	mn
5	Partial draw-down at each observation-well and time of observation due to each pumping well	ℓmn
6	Total draw-down at each observation-well and time of observation	ℓm
7	Discharge of each pumping well	n
8	Duration of each discharge at each time of observation	ℓn
9	Function u(r,t) for each radial distance and duration of discharge	ℓmn^2
10	Function W(u) for each value of u	ℓmn^2

In the light of these criteria, let us now examine the elements employed by WENZEL and GREENLEE in their generalization of the problem. These include the following:

Pumping wells	A, B, C,	N
Observation-wells	1, 2, 3	
Discharges	q_A, q_B, q_C	q_N
Durations of pumping	t_A, t_B, t_C	t_N
Radial distances	r_A, r_B, r_C	r_N
Functions u(r,t)	u_A, u_B, u_C	u_N
Functions W(u)	$W(u_A)$, $W(u_B)$, $W(u_C)$	$W(u_N)$
Partial draw-downs	s_A, s_B, s_C	s_N

In this scheme, the total number allowed for each kind of quantity is N, the number of pumping wells. For example, from well A only one radial distance r_A is specified without in any manner distinguishing between the multiplicity of radii, say r_{A1}, r_{A2}, r_{A3}, etc., from well A to each of the observation-wells, and so for the other quantities employed. The result is that either most of the items required in the analysis have been omitted entirely, or else a multiplicity of items of like kind but of different magnitude have been represented by one and the same algebraic symbol. In either case unintelligibility results.

Conclusion--In the present paper the authors have made a useful beginning to the treatment of the multiple-well problem. They have proceeded upon a physically-sound basis, and appear to have carried through successfully the numerical calculation of certain special cases. Due, however, to deficiencies of the type indicated above, they have not succeeded in accomplishing their major objective--the generalization of the single-well solution to the multiple-well case--and this problem must be regarded as still unsolved.

CHARLES V. THEIS (U. S. Geological Survey, Albuquerque, New Mexico)--The paper by WENZEL and GREENLEE develops further the use of the non-equilibrium formula to determine the fundamental parameters of an aquifer. The authors show how the coefficients of transmissibility and storage can be obtained by its use even when pumping is done simultaneously from a number of wells and in doing so they considerably increase its applicability to conditions met in the field.

It should be noted that the technique described in the paper is applicable not only to systems of real wells, but to combinations of real and imaginary wells also. The method is therefore applicable to pumping tests of wells near physical boundaries, such as those near the edge of alluvial valleys where, under proper conditions, the effect of relatively impermeable valley-walls can be simulated by an imaginary image-well (or group of wells) an equal distance beyond the contact between the alluvium and the bed-rock, or those in valleys near a river or irrigation-drain where the effect of the nearby source of water can be simulated under proper conditions by an image recharge-well an equal distance beyond the drain. The use of the technique for considering boundary-conditions may perhaps find more frequent application than for real systems of wells.

The pumping test at Oakes, North Dakota, furnishes a good example of the questions that rise constantly in the field as to how far to trust the theory with which one must work. The aquifer in this case was saturated to a depth of about 48 feet. The pumping wells went only about

13 feet below the water-table and penetrated only about 25 per cent of the saturated thickness. The duration of pumping was about 17 hours. Among the primary assumptions of the non-equilibrium formula are (1) the coefficient of transmissibility is constant, (2) the water is released instantaneously from storage as the water-table falls during pumping, and (3) the flow in the region of interest is horizontal. All of these assumptions were violated in some degree by the conditions of the test. The draw-down at the nearest observation-well was about three feet, which represents a decrease of thickness of saturated aquifer, and probably of transmissibility, of about eight per cent. It is quite doubtful if all of the water had drained from the sediments through which the water-table had fallen in the 17 hours of the test. The first observation-well was only 30 feet from the nearest pumped well; it is doubtful that there was no vertical component of movement of the water in the aquifer at this distance from the pumped wells. It is of some interest to examine the probable effects of these departures from the theoretical conditions.

The procedure in solving for the coefficients of transmissibility and storage consists essentially of matching the slope between two points [log s_1, log (r_1^2/t_1)] and [log s_2, log (r_2^2/t_2)] with the slope between two points on the "type"-curve [log $W(u_1)$, log u_1] and [log $W(u_2)$, log u_2]. Other points of the observed curve are plotted only as checks to the work. The type-curve becomes progressively steeper with increasing values of u and decreasing values of W(u). Hence, the greater the slope between the two points on the observation-curve, the smaller will be the value of W(u) indicated. If the thickness of saturation is made significantly smaller at the near observation-well, or if there is vertical movement of the water at the near observation-well, the draw-down in this well will be abnormally large. Hence, the plot of observed data will be abnormally steep and the point of matching the type-curve will be at lower values of W(u). The computed value of T will therefore be abnormally small. It will be noted that the same conditions make the values of the coefficient of transmissibility computed by Thiem's also too small for that coefficient varies in the contrary sense to the slope of the water-table between two points. Hence, the effects of thinning of the aquifer and probable vertical movement in the Oakes test tend to make the computed coefficient of transmissibility smaller than it should be. The probable size of the error is small, however, as these two disturbing factors appear to be small.

Of more general interest is the possible error introduced in the computations by the probable failure of the sediments to drain rapidly (or theoretically instantaneously) as the water-table falls during pumping. Experience has shown that the water-table generally falls more rapidly during the initial stages of pumping than is predicted by the non-equilibrium theory, but that it assumes relatively early near the well a position that is and remains parallel to its position after long periods of pumping, or, in other words, although the draw-downs are too large, the slope of the water-table between observation-wells near the pump remains constant. This is the reason Thiem's equation, which depends upon this slope, can be used near the well even when the cone of depression has not reached the equilibrium assumed in its theory. The non-equilibrium formula, however, depending as it does on the absolute value of the draw-down, might be expected to give rise to large errors in the computation of the transmissibility.

If the observational curve is made to coincide with the type-curve, their slopes will be equal at some point in the matched interval. The slope of the type-curve is [d log W(u)/d log u] which is equal to $[e^{-u}/W(u)]$. If we set s equal to the draw-down observed in an ideal aquifer true to all the assumptions of the non-equilibrium theory at the time t and the distance r, the slope of the observational curve will be [d log S/d log (r^2/t)] which is equal to $r^2 d\,s/[st\ d\,(r^2/t)]$ If we equate the two slopes and solve for W(u) we obtain

$$W(u) = [st\ e^{-u}\ d(r^2/t)/r^2 ds]$$

The coefficient of transmissibility will be

$$T_i = [W(u_i)/s_i] = [t\ e^{-u_i}\ d(r^2/t)/r^2 ds]$$

in which the subscripts i have been added to denote values obtained when the aquifer acts ideally.

If the water-table or other piezometric surface in an actual pumping test lies lower than it would be in an ideal aquifer because of the slow drainage of the overlying sediments, but is parallel to the position it would have in an ideal aquifer, as experience has shown it to be, the draw-down will be (s + a) at the distance r and the time t, in which a is an unknown constant. The slope of the observational curve will therefore be [d log (s + a)/d log (r^2/t)] which is equal to $[r^2 ds/(s + a)\ t\ d\,(r^2/t)]$. Equating to the type-curve

$$W(u_c) = [(s + a)\ t\ e^{-u_c}\ d(r^2/t)/r^2 ds]$$

and

$$T_c = [W(u_c)/(s + a)] = [t\, e^{-u_c}\, d(r^2/t)/r^2 ds]$$

in which the subscript c indicates values computed from the observations on the non-ideal aquifer.

The ratio of the computed to the ideal (correct) value of T is

$$T_c/T_i = e^{-u_c}/e^{-u_i}$$

In most pumping tests the values of u involved are small fractions. If the value of u is 0.1, the possible error in the computed coefficient of transmissibility is about ten per cent and if it is 0.01, the possible error is about one per cent. Hence, the application of the non-equilibrium formula to data from several wells at the same time, even after a comparatively short pumping period, is likely not to introduce serious errors in the computation of the coefficient of transmissibility. The possible error may be estimated by roughly calculating the value of u from probable values of transmissibility and storage.

The error in the computation of the coefficient of storage is generally much greater than that of transmissibility. The figure obtained for storage depends upon the value of u read from the type-curve. This value changes very rapidly with slight changes of slope. With the same observational data that yield an error of only ten per cent in transmissibility, the error in the storage-coefficient can be 90 per cent. This condition probably underlies the empirical observation that independent data in any one pumping test generally yield values for transmissibility that are quite alike but values for storage that are rather divergent.

L. K. WENZEL and A. L. GREENLEE--Mr. Hubbert points out that the graphical method as it is applied to a single discharging-well is credited to C. V. THEIS by a "personal communication." This reference [2] has been changed in the final draft of the paper to indicate that the method was described by Theis in an unpublished manuscript of the Geological Survey and hence Mr. Hubbert's statement is no longer strictly applicable. Unfortunately, the manuscript referred to concerns confidential work relating to military activities and references to it must necessarily be ambiguous.

CORRELATION OF GROUND-WATER LEVELS AND PRECIPITATION ON LONG ISLAND, NEW YORK

C. E. Jacob

(Published with the approval of the Director, U. S. Geological Survey)

PART I—THEORY

(Abstract--Long Island simulates in a general way an aquifer in the form of an infinite strip confined between parallel boundaries at constant head (sea-level), over which recharge from precipitation is assumedly uniform. The non-steady flow of water in this idealized system is analyzed, assuming provisionally that the effective thickness of saturated beds below sea-level is great compared to the maximum height of the water-table above sea-level. The rate of accretion to the water-table is assumed to vary discontinuously, supposedly being constant for each of the successive periods (yearly or monthly) and proportional to the average rate of precipitation during that period. The decay of the water-table profile, beginning with any one of the succession of superposed non-steady states, is shown to follow in general a relation composed of terms varying with time as $\exp(-t/t_o)$, in which t_o is a function of the effective porosity, the thickness and the transmission-constant of the aquifer. This exponential curve may be approximated by a parabola which is used to determine values of "effective average rate of precipitation" from published records of annual or monthly precipitation. By the "effective average rate of precipitation" at any time is meant that rate of precipitation which, had it been maintained uninterruptedly throughout the past, would have produced the same water-table profile as actually existed at that particular time. It is demonstrated that the effective average rate of precipitation may be determined also simply by cumulating departures from progressive averages of precipitation, multiplying the values thus determined by a known rational coefficient, and adding the appropriate initial value of effective average precipitation.)

In attempts to correlate precipitation-data with records of ground-water level or stream-flow it has long been the custom to cumulate departures of the precipitation from the "normal" or mean. So-called "residual mass-curves" have been drawn showing the excess or deficiency of rainfall over the mean for a fixed period. Early work along this line was done in connection with the Wiener Neustadt Project for the well-water supply of Vienna [see 1 of "References" at end of paper].

More recently progressive averages have also been used. For example, a publication on rainfall and runoff [2] gives graphs showing the "annual and ten-year progressive average precipitation" for selected drainage-basins in the United States. In most cases on visual comparison the ten-year progressive average precipitation shows general conformity with the ten-year progressive average runoff.

It is the intent of this paper to justify use of the cumulative departure from progressive averages for correlating precipitation with ground-water levels and with "ground-water flow" in streams, thus combining in a sense the idea of cumulating departures with the idea of using progressive averages. To the writer's knowledge, the first attempts along this line in hydrology were made by LEGGETTE [3]. In studying fluctuations of the ground-water level on Long Island, New York, Leggette cumulated departures of precipitation from ten-year progressive monthly averages. That is, he took the difference between the precipitation during a given month (average for two stations--New York City and Setauket, Long Island) and the average precipitation for the ten preceding months of the same name, cumulated such differences, and compared the resulting graph with an average water-level graph [4]. With the scales of plotting arbitrarily fixed, general overall conformity between the two graphs is suggested for the last nine years (1932-40). Leggette states that "a comparison between cumulative departures based on three-year progressive averages and cumulative departures based on ten-year progressive averages indicates that the ten-year progressive averages are somewhat better for showing the relation between precipitation and ground-water levels." As discussed in Part II of this paper [see abstract at end of Part I], it has since been found that cumulative departures based on 25-year progressive averages correlate best with ground-water levels on Long Island.

This paper is an extension of the work begun by Leggette. It is demonstrated in Part I that by multiplying the cumulative departures from progressive averages by a predetermined coefficient and adding each in turn to a constant, there may be determined values of the "effective average rate of precipitation." In the absence of large variations from year to year in the ratios to precipitation of the surface-runoff and of the loss due to evaporation and transpiration, a graph of the "effective average rate of precipitation" theoretically should conform with a plotting of annual mean water-levels. By this means an arbitrary step in scale adjustment is eliminated. Further, it is shown that the length of the optimum period of adjustment (in this case empirically found to be 25 years) is related to certain physical characteristics of the flow-system, most of which are quite readily determined.

Long Island, the scene of many early ground-water studies in the United States, affords an excellent field for investigation. That part of the Island that lies in Nassau County and western Suffolk County may be considered to represent part of an infinite strip of land of uniform width. The parallel boundaries of this infinite-strip aquifer are maintained virtually at constant zero-head, that is, at sea-level. In developing the theory it will be convenient to make further simplifying assumptions in regard to the hypothetical aquifer substituted for the actual island. Discussion of the practical significance of these assumptions is reserved for Part II, where the effect of the physiography and geology on water-levels is considered.

Recharge from precipitation is assumed uniform over the width of the strip. Assuming now that the effective thickness of saturated beds below sea-level is great compared to the maximum height of the water-table above sea-level so that the total thickness may be regarded as constant, the equation for the steady-state profile of the water-table may be expressed in the simplest terms. The problem is a two-dimensional one. Take as origin of coordinates a point at sea-level on one edge of the strip (see Fig. 1-A). Let the width of the strip be 2a. Then $x = 0$ and $x = 2a$ represent the boundaries of the strip. Let h_o be the ordinate of the water-table profile, or the head, which is a function of x. Because of symmetry of the profile, at $x = a$ there is no lateral flow and the slope of the water-table is zero. At any point x the rate of lateral flow per unit normal thickness is

$$q = -Km(dh_o/dx) = W(x - a) \qquad (1)$$

where m is the constant thickness of saturated beds, K is the transmission-constant or "coefficient

of permeability" (discharge per unit-area per unit hydraulic gradient), and W is the rate of accretion to the water-table of water derived from precipitation. W has the dimensions of a velocity.

Integrating equation (1), after multiplying through by dx

$$T \cdot h_o = W(ax - x^2/2) + C$$

Here T, called "transmissibility," is the product of the transmission-constant, K, and the thickness, m. It is seen that to satisfy the condition $h_o = 0$ at $x = 0$, the constant of integration, C, must be zero. Therefore, the equation of the steady-state profile is

$$h_o = (W/T)(ax - x^2/2) = (a^2W/2T)(2x/a - x^2/a^2) \qquad (2)$$

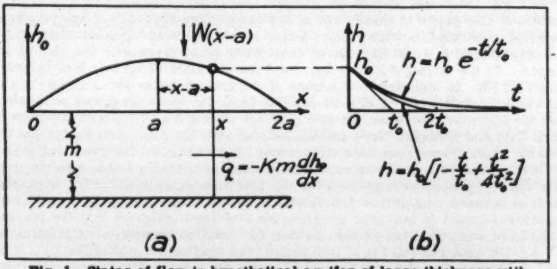

Fig. 1--States of flow in hypothetical aquifer of large thickness with uniform accretion from precipitation: (a) Steady-state profile; (b) decay of profile in non-steady state

This is the particular solution of the fundamental differential equation

$$(d^2h_o/dx^2) = -(W/T) \qquad (3)$$

obtained by differentiating equation (1), with boundary-conditions $h_o = 0$ at $x = 0$ or at $x = 2a$, and $(dh_o/dx) = 0$ at $x = a$.

The parabola $(2x/a - x^2/a^2)$ may be developed in a sine-series, whence

$$\left.\begin{aligned} h_o = (a^2W/2T)(32/\pi^3)[&\sin(\pi x/2a) + (1/27)\sin(3\pi x/2a) \\ &+ (1/125)\sin(5\pi x/2a) + \ldots] \end{aligned}\right\} \qquad (4)$$

Consider now the decay of this steady-state profile in the absence of recharge, W instantaneously becoming zero. Let h be the ordinate of the profile in the non-steady state, and let S be the "coefficient of storage," in this case equal to the specific yield. The differential equation [5] to be satisfied is

$$(\partial h/\partial t) = (T/S)(\partial^2 h/\partial x^2) \qquad (5)$$

with conditions $h = 0$ at $x = 0$ or at $x = 2a$ for all values of t and $h = h_o(x)$ at $t = 0$.

The particular solution sought here is

$$\begin{aligned} h = (a^2W/2T)(32/\pi^3)[&\exp(-\pi^2Tt/4a^2S)\cdot\sin(\pi x/2a) + \\ &+ (1/27)\exp(-9\pi^2Tt/4a^2S)\cdot\sin(3\pi x/2a) + \\ &+ (1/125)\exp(-25\pi^2Tt/4a^2S)\cdot\sin(5\pi x/2a) + \ldots] \end{aligned} \qquad (6)$$

Instead of following the decay of the water-table profile from $h(x) = h_o(x)$ to $h(x) = 0$, it will be desired to follow the decay from the initial steady state, corresponding to a constant rate of

accretion, W, to a second steady state, corresponding to a rate of accretion differing from the first by a small amount ΔW. Then the non-steady profile of the water-table is given by

$$h' = (1 + \Delta W/W)h_o - (\Delta W/W)h = h_o + (\Delta W/W)(h_o - h) \quad (7)$$

where h_o is given by equation (4) or equation (2), and where h is given by equation (6). Equation (7) is the particular solution of the equation

$$(\partial^2 h'/\partial x^2) = -(W + \Delta W)/T + (S/T)(\partial h'/\partial t) \quad (8)$$

with boundary-conditions $h' = 0$ at $x = 0$ or at $x = 2a$ for all values of t, and $h' = h_o$ for $t = 0$, satisfying also the condition $h' = (1 + \Delta W/W)h_o$ for $t \to \infty$.

Because equation (8) is linear, it is permissible to superpose non-steady states described by equation (7). Thus theoretically it is possible in the limit to analyze the effect of rates of accretion which vary continuously. However, in correlating actual precipitation-records with water-level data, it will be desirable to consider the rate of accretion as varying discontinuously. Also, it will be found permissible in dealing with Long Island to assume as a first approximation that the rate of accretion is constant for each of the successive (yearly) periods and proportional to the average rate of precipitation during that period. In other words, $W_n \sim R_n$, where R_n is the average rate of precipitation during the n^{th} period (n^{th} year).

To simplify further the analysis which follows, neglect all terms after the first in the series of equation (6). Then

$$h = h_o \cdot \exp(-\pi^2 Tt/4a^2 S) \quad (9)$$

and

$$h_o = (a^2 W/2T)(32/\pi^3) \cdot \sin(\pi x/2a) \quad (10)$$

In equation (9) put $(4a^2 S/\pi^2 T) = t_o$ and expand $\exp(-t/t_o)$ in a series

$$(h/h_o) = 1 - (t/t_o) + (t^2/2t_o^2) - (t^3/6t_o^3) + (t^4/24t_o^4) - \ldots \quad (11)$$

It will be found expedient to replace this exponential curve by the parabola

$$(h/h_o) = 1 - (t/t_o) + (t^2/4t_o^2) \quad (12)$$

terminating at $t = 2t_o$ (see Fig. 1-B).

The non-steady flow of water in the ideal system postulated above has been analyzed under assumptions other than those taken--assumptions which fit the particular case more closely perhaps. For instance, it may be considered (1) that the sole of the aquifer is not impermeable as tacitly assumed above or (2) that m is not large compared to the average h_o, that the total thickness varies appreciably with x [6]. Such assumptions lead to equations more complex than, but sufficiently near in form to, the foregoing relations to allow, for the present analysis, that they be approximated by equation (12). It is thought that its greater instructional value justifies treatment of the simplest case to the exclusion of the others at this point. Moreover, regardless of the details of the theory there is inevitably an empirical adjustment to be made to fit it to the factual data.

Rewriting equation (12) to express h as a function of t

$$h(t) = h_o[1 - (t/t_o) + (t^2/4t_o^2)] \quad (13)$$

This curve may be employed to determine values of the "effective average rate of precipitation" from past records of precipitation. By the "effective average rate of precipitation" at any given time is meant that rate of precipitation which, had it been maintained uninterruptedly throughout the past, would have been effective in producing the same water-table profile as actually existed at that particular time. It is assumed, as before stated, that over a sufficiently long period the rate of accretion to the water-table is proportional to the rate of precipitation ($W \sim R$).

Designating the effective average rate of precipitation at time t by $\bar{R}$

$$\bar{R} = \bar{R}(t) = \int \Phi \, dR_{t-} \tag{14}$$

where Φ is given by

$$\Phi = 1 - [h(\tau)/h_o]$$

$(t - \tau)$ being the time of occurrence of precipitation-rate R (see Fig. 2).

By equation (13)

$$\Phi = (\tau/t_o) - (\tau^2/4t_o^2) \tag{15}$$

Hence

$$\bar{R} = R_{(t-2t_o)} - \int_0^{2t_o} [(\tau/t_o) - (\tau^2/4t_o^2)] \, (\partial R/\partial\tau)_{(t-\tau d\tau)} \tag{16}$$

Ordinarily the limits of integration here would be zero and infinity, that is, if the function Φ were derived from the exponential relation of equation (9). However, for practical considerations the period of integration is purposely terminated, and there appears in equation (16) the constant $R_{(t-2t_o)}$.

Usually R is not a known continuous function and consequently $(\partial R/\partial\tau)$ is not expressible in integrable form. Therefore, it is necessary to proceed by analyzing finite differences. The interval $2t_o$ is divided into k periods of equal length Δt (see Fig. 3), τ is set equal to $i\Delta t$, and $t = n\Delta t$. Then $dR_{(t-\tau)} = -(\partial R/\partial\tau)_{(t-\tau d\tau)}$ is replaced by

$$\Delta R_{(n-i)} = R_{(n-i+1)} - R_{(n-i)} \tag{17}$$

is replaced by a series of coefficients having values less than unity as in equation (18).

$$C_{(n-i)} = [2ik - i(i - 1)]/[k(k + 1)] \tag{18}$$

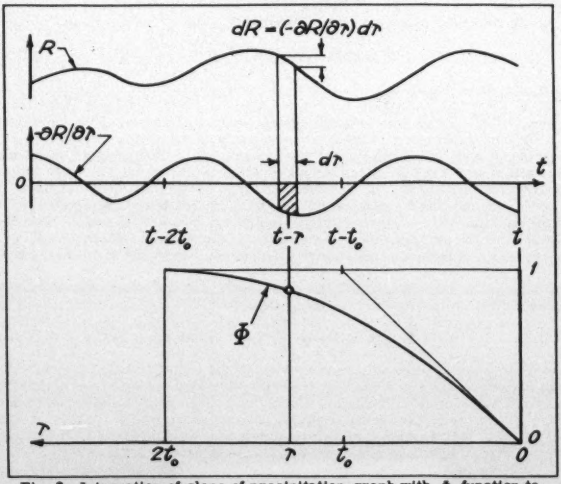

Fig. 2--Integration of slope of precipitation-graph with Φ-function to determine effective average rate of precipitation at time t

To confirm the equivalence of $C_{(n-1)}$ and Φ, make the substitutions $k = (2t_o/\Delta t)$ and $i = (\tau/\Delta t)$ and pass to the limit

$$\text{Lim (as } \Delta t \to 0) C_{(n-1)} = (2\tau 2t_o - \tau^2)/(2t_o)^2 = (\tau/t_o) - (\tau^2/4t_o^2) = \Phi$$

Replacing the integral sign of equation (16) by a summation sign with properly chosen limits

$$\bar{R}_n = R_{(n-k+1)} + \sum_{i=1}^{(k-1)} C_{(n-1)} (R_{(n-1+1)} - R_{(n-1)}) \tag{19}$$

Observing that $C_{(n-k)} = 1$ and that $C_n = 0$, it is seen that

$$\bar{R}_n = \sum_{i=1}^{k} R_{(n-i+1)}(C_{(n-i)} - C_{(n-i+1)}) \tag{20}$$

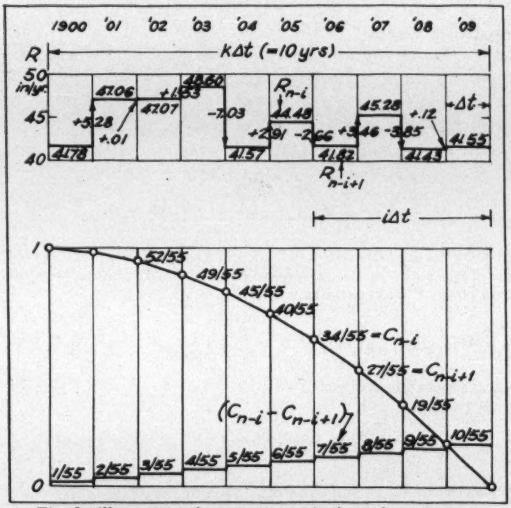

Fig. 3--Illustration of summation procedures for computing effective average rate of precipitation at end of year 1909 (compare with Table 1)

This is equivalent to the integral relation $\bar{R} = \int R \cdot d\Phi$.

Equation (20) may be simplified further. For, as is easily demonstrated,

$$C_{(n-i)} - C_{(n-i+1)} = 2(k - i + 1)/k(k + 1) \tag{21}$$

Then

$$\bar{R}_n = \sum_{i=1}^{k} R_{(n-i+1)} \cdot 2(k - i + 1)/k(k + 1) \tag{22}$$

This provides a convenient method of determining the effective average rate of precipitation for small values of k, though the computations become rather laborious for large values of k.

However, there is a still shorter method than that given by equation (22). For, as will be shown, the effective average rate of precipitation may be determined also simply by cumulating the departures from progressive averages of the rate of precipitation, multiplying the values thus determined by a known rational coefficient dependent on k, and adding the appropriate initial value of effective average rate of precipitation.

The average rate of precipitation for k years preceding the m^{th} year is $(1/k) \sum_{j=1}^{k} R_{(m-j)}$. The departure of the rate of precipitation during the m^{th} year from the average for the k preceding years is $R_m - (1/k) \sum_{j=1}^{k} R_{(m-j)}$.

Cumulating such departures from progressive averages, beginning with the p^{th} year, one gets

$$(1/k) \sum_{m=p+1}^{n} [k \cdot R_m - \sum_{j=1}^{k} R_{(m-j)}]$$

It is now required to show that

$$\bar{R}_n = [2/(k+1)] (1/k) \sum_{m=p+1}^{n} [k \cdot R_m - \sum_{j=1}^{k} R_{(m-j)}] + \bar{R}_p \qquad (23)$$

where $[2/(k+1)]$ is the "rational coefficient" referred to previously. $\bar{R}_p$ is "the appropriate initial value of effective average rate of precipitation," which may be computed from equation (22) by substituting p for n

$$\bar{R}_p = \sum_{i=1}^{k} R_{(p-i+1)} \cdot 2(k-i+1)/k(k+1) \qquad (24)$$

After transposing the $\bar{R}_p$ to the left-hand side of equation (23), substitute for $\bar{R}_n$ the expression given by equation (22), and for $\bar{R}_p$ the expression given by equation (24). Then cancel out the $[2/k(k+1)]$. This leaves to be demonstrated that

$$\sum_{i=1}^{k} (R_{(n-i+1)} - R_{(p-i+1)}) (k-i+1) = \sum_{m=p+1}^{n} [k \cdot R_m - \sum_{j=1}^{k} R_{(m-j)}]$$

The right-hand member is equal to

$$\sum_{m=p+1}^{n} \sum_{j=1}^{k} (R_m - R_{(m-j)}) = \sum_{i=1}^{k} \sum_{m=p+1}^{n} (R_m - R_{(m-i)})$$

which may be expanded to give $\sum_{i=1}^{k} (R_{(p+1)} - R_{(p-i+1)} + R_{(p+2)} - R_{(p-i+2)} + \cdots$

$\cdots + R_{(n-1)} - R_{(n-i-1)} + R_n - R_{(n-i)})$.

Assigning successive values to i

$(R_n - R_p) +$

$(R_n - R_p + R_{(n-1)} - R_{(p-1)}) +$

$(R_n - R_p + R_{(n-1)} - R_{(p-1)} + R_{(n-2)} - R_{(p-2)}) + \cdots +$

$(R_n - R_p + R_{(n-1)} - R_{(p-1)} + \cdots + R_{(n-k+2)} - R_{(p-k+2)}) +$

$(R_n - R_p + R_{(n-1)} - R_{(p-1)} + \cdots + R_{(n-k+2)} - R_{(p-k+2)} + R_{(n-k+1)} - R_{(p-k+1)})$

Combining like terms

Table 1--Ten-year effective average rate of precipitation at the end of the year 1909, computed first by means of equation (19) and then by means of equation (22), based on records of precipitation at the Battery in New York City

Year (n - i)	(i)	R_{n-i}	Long method [using eq. (19)] $(R_{n-i+1} - R_{n-i})C_{n-i}$	Short method [using eq. (22)] $(R_{n-i+1})(11-i)/55$
		in/yr		
1899	10(=k)	.....	.....	41.78(1/55) = 0.76
1900	9	41.78	5.28(54/55) = 5.18	47.06(2/55) = 1.71
1901	8	47.06	0.01(52/55) = 0.01	47.07(3/55) = 2.57
1902	7	47.07	1.53(49/55) = 1.36	48.60(4/55) = 3.53
1903	6	48.60	-7.03(45/55) = -5.75	41.57(5/55) = 3.78
1904	5	41.57	2.91(40/55) = 2.12	44.48(6/55) = 4.85
1905	4	44.48	-2.66(34/55) = -1.64	41.82(7/55) = 5.32
1906	3	41.82	3.46(27/55) = 1.70	45.28(8/55) = 6.59
1907	2	45.28	-3.85(19/55) = -1.33	41.43(9/55) = 6.78
1908	1	41.43	0.12(10/55) = 0.02	41.55(10/55) = 7.56
1909	0	41.55	.....	.....
Σ		.....	..... +1.67	..... 43.45
		$\bar{R}_{09}$ = +1.67 + 41.78 = 43.45		= $\bar{R}_{09}$

Table 2--Ten-year effective average rate of precipitation at the end of the year 1900 computed by means of equation (24), and at the end of each succeeding year up to 1909 computed by means of equation (23), based on records of precipitation at the Battery in New York City

Year (p-i)	(i)	R_{p-i}	Using eq. (24) $(R_{p-i+1})(11-i)/55$
		in/yr	
1890	10(=k)	.....	41.44(1/55) = 0.75
1891	9	41.44	38.90(2/55) = 1.42
1892	8	38.90	53.01(3/55) = 2.89
1893	7	53.01	44.17(4/55) = 3.21
1894	6	44.17	35.73(5/55) = 3.25
1895	5	35.73	37.99(6/55) = 4.15
1896	4	37.99	44.27(7/55) = 5.63
1897	3	44.27	45.12(8/55) = 6.56
1898	2	45.12	42.06(9/55) = 6.88
1899	1	42.06	41.78(10/55) = 7.60
Σ	.....	.....	..... 42.34 = $\bar{R}_{00}$

Year (n)	(i)	Rate of precipitation	10-yr progressive average	Departure from prog. average	Cumulative departure	Cum. dep. × (2/11)	Effective average rate of precipitation, $(\bar{R}_n)$
		in/yr					in/yr
1900	0	41.78	.....	.....	.....	.....	42.34
1901		47.06	42.45	4.61	4.61	0.84	43.18
1902		47.07	43.01	4.06	8.67	1.58	43.92
1903		48.60	43.83	4.77	13.44	2.44	44.78
1904		41.57	43.38	-1.81	11.63	2.11	44.45
1905		44.48	43.13	1.35	12.98	2.36	44.70
1906		41.82	44.00	-2.18	10.80	1.96	44.30
1907		45.28	44.38	0.90	11.70	2.13	44.47
1908		41.43	44.48	-3.05	8.65	1.57	43.91
1909		41.55	44.11	-2.56	6.09	1.11	43.45

$$k(R_n - R_p) + (k - 1)(R_{(n-1)} - R_{(p-1)}) + (k - 2)(R_{(n-2)} - R_{(p-2)}) + \ldots$$
$$+ 2(R_{(n-k+2)} - R_{(p-k+2)}) + (R_{(n-k+1)} - R_{(p-k+1)})$$

But this is identical to

$$\sum_{i=1}^{k} (k - i + 1)(R_{(n-i+1)} - R_{(p-i+1)})$$

thus proving the proposition at hand.

The different procedures that may be followed in computing values of the effective average rate of precipitation are illustrated in Tables 1 and 2 and in Figure 3, using data obtained by the United States Weather Bureau at the Battery in New York City. A value of ten is assigned to k. Table 1 gives two equivalent methods of computing the ten-year effective average rate of precipitation at the end of the year 1909. First the "long method" is given, following equation (19), in which finite increments in the rate of precipitation are multiplied by the appropriate coefficients $C_{n-i} = [10i - i(i - 1)/2]/55$ and then summed up and added to the value of R for the $(n - 9)^{th}$ year (the year 1900). The "short method," following equation (22), involves merely summing up products of rates of precipitation and appropriate differences between successive coefficients: $(C_{(n-i)} - C_{(n-i+1)}) = (11 - i)/55$.

In Table 2 the ten-year effective average rate of precipitation at the end of the year 1900 is computed by means of equation (24), "short method". Values of the ten-year effective average rate of precipitation at the end of succeeding years are computed by means of equation (23). First, values of ten-year progressive average precipitation are determined. Then, the departures of the actual annual rates of precipitation from the progressive averages are determined and cumulated. The cumulated departures are then multiplied by $[2/(k + 1)] = (2/11)$ and added to the effective average for 1900 ($\bar{R}_{00}$).

It is seen that the effective average for 1909, determined by three different procedures, is 43.45 inches per year. Computations shown in Tables 1 and 2 were carried out on a calculating machine to one place beyond what is tabulated. Accordingly, minor adjustments were made in rounding off the figures in the last columns of both Tables.

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Part II--Correlation of data

Abstract--Records of rainfall at the Battery in New York City and at Setauket, Long Island, are analyzed by the procedure outlined in Part I. In determining progressive averages, periods of 10, 15, 20, 25, 30, and 40 years are used. Values of the effective average rate of precipitation are correlated with composite average water-levels for the periods 1912-18 and 1932-41 based on records of 14 wells in Nassau County and western Suffolk County. The best correlation is obtained with the 25-year effective average, a fair agreement being shown with annual mean water-levels. Analysis and correlation of the same data on a 300-month basis permit an approximate evaluation of the relative magnitude of the loss due to transpiration and evaporation. Knowledge of the approximate value of this fundamental time-constant (25 years or 300 months) permits a crude checking of the probable values of other factors such as the permeability and specific yield of the beds and their effective thickness, and the average annual rate of accretion to the water-table.

For the purpose of comparison, correlations of water-levels are also made using (1) progressive averages of precipitation and (2) cumulative departures from fixed averages--two methods

of presentation now commonly used.

The "effective average," determined by cumulating departures from progressive averages, is suggested as a tool for the analysis also of long-term records of "ground-water flow" in streams.

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A FREQUENCY-METHOD OF EVALUATING GROUND-WATER LEVELS

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Water-levels in wells, which are utilized by the hydrologist as a measure of ground-water storage, customarily are measured in terms of distance below a convenient measuring point and expressed with reference to a fixed datum. Datum-planes or surfaces of several types have been used--each serving some particular purpose advantageously. These include: "Planes" of regional extent, such as mean sea-level; irregular surfaces defining a particular hydrologic condition, such as low-water level (if known) or the water-level on some particular date; and local reference-planes at each observation-well, such as a horizontal plane through the measuring point or at the average height of the land-surface. Recently the Geological Survey has considered the standard use of a land-surface datum, precisely defined for each observation-well. This procedure has the practical advantage that the water-levels can be recorded in final form as soon as the initial measurement is made, without leveling to establish a regional datum or waiting to accumulate sufficient data for defining a particular hydrologic condition.

Obviously, the practices just outlined are adequate and convenient for the factual water-level record. With respect to full interpretation of hydrologic conditions in an area, however, such records have certain inherent disadvantages. Two disadvantages become apparent when water-levels in a large number of wells are averaged to determine a mean level for a basin or area; they become critical when an observation-well must be dropped from or added to the group for which past average levels have been derived.

One disadvantage arises from the fact that the relation between the datum-plane or surface and the central tendency of the measured water-levels is not the same in all wells. "Central tendency" is a general term used by statisticians for measures such as mode, mean, and median; to some extent it is equivalent to the much-abused term "normal" [see 1 of "References" at end of paper].

Another disadvantage arises because, when expressed in feet or some other unit of linear measure, the spread of the measured water-levels in any one observation-well may differ greatly from the spread of levels in any other observation-well in the same basin or area. "Spread" is a general term used by statisticians for average deviation, standard deviation, coefficients of sorting, and other measures of the scatter of data about the central tendency [1]. Thus, water-levels in one well may fluctuate through a range five times that in another well in the same area. If the levels from two such wells in a group are given equal weight in calculating an average, the well having the larger spread will influence the average about five times as much as the other well. MERRIAM has discussed this disadvantage and gives illustrative examples [2]. With this variation in mind reconsider the effect of using a local low-water datum. With respect to such a datum, the central tendency of the water-levels in a well with large spread may be considerably higher than the central tendency for a well with only moderate spread.

The present paper suggests a statistical method of evaluating ground-water levels that overcomes some of the disadvantages just discussed. Statistical theory already has been used to advantage in sedimentary petrography [3] and in the analysis of the magnitude and frequency of floods [4]. To facilitate use of the method an effort has been made to simplify the statistical treatment to the utmost without sacrificing the degree of accuracy necessary for an analysis of hydrologic conditions. The statistical analysis here outlined must be based on a record sufficiently long to define the frequency at which any particular water-level recurs; at least five years of record probably is necessary. Each record should consist of measurements taken at about equal intervals of time. Monthly measurements can be used conveniently; more frequent measurements may needlessly prolong the statistical treatment. By means of this method water-levels are treated in terms of the frequency of their occurrence, as is developed in the following example.

Table 1--Frequency-distribution of monthly water-level measurements in Well US 68, August 1937 to July 1942

(No measurements in 6 of the 60 months)

Water-level class-interval, feet above a local low-water datum[a]	Tallies	Number of tallies	Frequency	Cumulative frequency
			pct	pct
4.5 - 5.0	1	1	2	100
4.0 - 4.5	111	3	6	98
3.5 - 4.0	111	3	6	92
3.0 - 3.5	11111111	8	15	86
2.5 - 3.0	11111	5	9	71
2.0 - 2.5	1111111111	10	18	62
1.5 - 2.0	1111111111	10	18	44
1.0 - 1.5	1111111	7	13	26
0.5 - 1.0	111111	6	11	13
0.0 - 0.5	1	1	2	2
Totals	.....	54	100	.....

[a]The nature of the datum used in the water-level record is immaterial to the method of treatment.

The first step in the statistical treatment is a tally sheet of past water-level measurements. able 1 shows such a frequency-distribution for Well US 68 at Tacoma, Washington. The basic iata used for this well consist of monthly water-level measurements from August, 1937, through July, 1942; the range of water-level fluctuations in this period was about five feet. In order to have an adequate number of classes, the five-foot range is divided into class intervals of 0.50 foot and each water-level measurement is tallied opposite the class in which it falls. A few characteristics of the well are clarified by Table 1. Thus, the principal mode, or the water-level that has recurred most frequently, lies between 1.5 and 2.5 feet above the low-water datum, closer to the extreme low level than to the extreme high level. A secondary mode occurs between 3.0 and 3.5 feet. The length of the several tally-rows shows approximately the probable frequency at which any particular level will recur. For example, a level between 0.5 and 1.0 foot occurs about twice as often as one between 4.0 and 4.5 feet.

In Table 1, the frequency is the percentage of the term of record during which the ground-water level was within each class-interval. If the term of record is sufficiently great, this percentage defines the long-term probability of each particular level recurring. These percentage-frequencies are cumulated beginning with the class-interval that represents the lowest level. Thus, the cumulative frequency is the percentage of time that water-levels occur below the higher limit of each class-interval. The next step is to plot the cumulative frequency on arithmetic-probability paper (Fig. 1). A point is plotted for the higher limit of each class-interval and for the corresponding cumulative frequency, using the arithmetic scale for water-levels and the probability-scale for frequency. Arithmetic-probability paper is so constructed that a "normal" probability-distribution plots on it as a straight line. The points plotted for a particular set of water-level data may define a straight line or a gentle curve.

To determine fundamental characteristics of the frequency-distribution of the water-levels, a straight line is then drawn through the two points at which the ordinates of 15.9 and 84.1 per cent are crossed by the line or curve defined by the plotted points. Then the mean water-level is scaled from the intersection of this straight line with the ordinate of 50 per cent. The standard deviation is taken as one-half the difference between the water-levels corresponding to 15.9 and 84.1 per cent. OTTO has described this method as applied to the frequency-distribution of the size of particles in sediments and has shown that it yields acceptable values for the mean and for the standard deviation, even though the set of data has a moderately skewed distribution and defines a gentle curve rather than a straight line on the probability paper [5].

Figure 1 includes probability-graphs for four key observation-wells of the Geological Survey in Oregon and Washington--wells that represent considerable diversity in conditions of groundwater occurrence. Well US 108, situated on the alluvial fan of the Walla Walla River in Oregon, affords a critical test of the method because its water-level fluctuates widely and rapidly in response to flash runoff in the river, making the frequency-distribution of its water-levels moderately skewed. Table 2 indicates that the values for arithmetic mean water-level and for standard

Table 2--Comparison of values for arithmetic mean water-level and for standard deviation derived graphically and by calculation

Well	Arithmetic mean water-level		Standard deviation	
	Calculated	Interpolated from Fig. 1	Calculated	Interpolated from Fig. 1
US 108, Walla Walla Basin, Oregon	15.64	16.1	8.44	8.8
US 70, Spokane, Washington	8.80	9.2	4.13	4.3
US 69, Cashmere, Washington	5.90	6.2	2.17	2.1
US 68, Tacoma, Washington	2.31	2.3	1.05	1.1

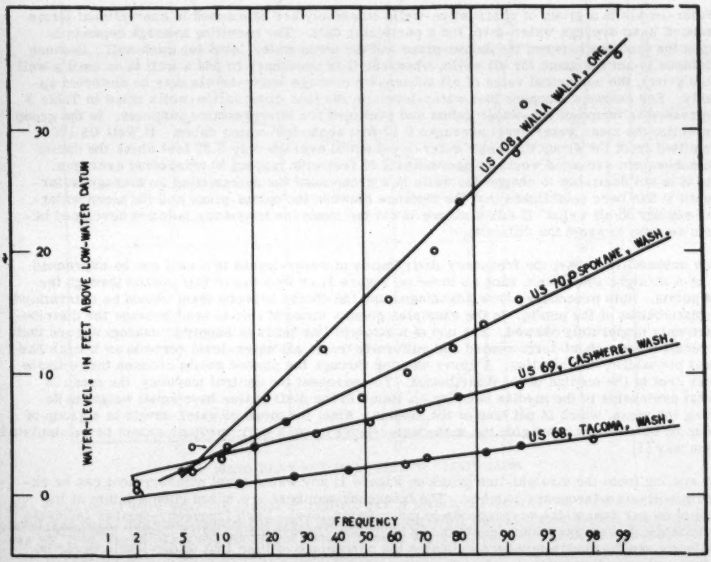

Fig. 1--Graph showing frequency of water-level occurrence in four observation-wells

deviation determined by the graphical method just outlined are approximately equal to the corresponding values derived from the more rigorous but longer computation method usually used by statisticians [1]. This conformity indicates that Otto's graphical method gives accurate values for the mean and standard deviation when applied to water-level measurements in wells.

For each of the four wells, Table 3 gives values of the calculated mean water-level with respect to low-water datum, land-surface datum, and sea-level datum. It also gives the frequency-number determined by the interesection of the straight-line graph on probability paper and the calculated mean water-level. Expressed in feet with respect to the several datum planes the values range widely; expressed in terms of frequency-numbers, however, they are nearly equal for the four wells. When water-levels are expressed adequately for comparison, the calculated mean water-levels should be equal because they clearly represent similar water-levels in the different wells.

Table 3--Calculated mean water-level expressed in conventional terms and in terms of frequency-number

Well	Mean water-level			
	Feet above low-water datum	Feet below land-surface datum	Feet above sea-level datum	Frequency-number from Figure 1
US 108, Walla Walla Basin, Oregon	15.64	28.11	901.64	49
US 70, Spokane, Washington	8.80	145.62	1,910.27	49
US 69, Cashmere, Washington	5.90	15.10	764.90	48
US 68, Tacoma, Washington	2.31	36.03	231.35	51

Water-levels in a group of observation-wells commonly are expressed in conventional terms and reduced to an average water-level for a particular date. The resulting average depends in part upon the distance between the datum-plane and the mean water-level for each well. Because this distance is not the same for all wells, whenever it is necessary to add a well to or omit a well from the group, the numerical value of all subsequent average water-levels may be distorted appreciably. For example, suppose that water-levels in the four observation-wells noted in Table 3 are expressed in terms of low-water datum and averaged for interpretative purposes. In the group of four wells, the mean water-level averages 8.13 feet above low-water datum. If Well US 108 were omitted from the group the mean water-level would average only 5.67 feet above the datum and all subsequent averages would be decreased 2.46 feet with respect to antecedent averages. Clearly it is not desirable to change the wells in a group used for determining an average water-level until it has been established that the distance between the datum-plane and the mean water-level is similar in all wells. If this distance is not the same the frequency-notation developed beyond can be used to avoid the difficulty.

On probability-paper, the frequency-distribution of water-levels in a well can be expressed either by a straight-line graph, such as those on Figure 1, or by a curve that passes through the plotted points. Both procedures have advantages and the choice between them should be determined by the distribution of the points. In the examples given a straight line is used because the distributions are only moderately skewed. The use of a straight line tends to suppress random errors that might result from a short-term record and uniformly treats all water-level records as if each has a normal probability-distribution. A curve passing through the plotted points crosses the ordinate of 50 per cent at the median of the distribution. To represent the central tendency, the mean is somewhat preferable to the median because all items in the distribution have equal weight in determining the mean, which is not true of the median. Also, the mean of water-levels in a group of wells can be obtained by averaging the mean water-level in each well; medians cannot be manipulated the same way [1].

By scaling from the straight-line graph on Figure 1, any water-level measurement can be expressed readily as a frequency-number. The frequency-numbers are based upon a datum at the ordinate of 50 per cent which corresponds to mean water-level. Each frequency-number indicates the percentage of time that water-levels occur below the corresponding water-level. The difference between two frequency-numbers indicates the percentage of time that water-levels occur between the corresponding water-levels. For many interpretative purposes, frequency-numbers can be used as readily as the measured water-levels.

Figures 2 and 3 show hydrographs for the four wells in terms of height above low-water datum and in terms of frequency-numbers as just defined. For interpretative purposes the frequency-hydrographs show certain critical features not shown by the height-hydrographs because each point of the frequency-hydrograph is fixed by its relation to the past distribution of water-levels in the well. For example, in feet above low-water datum, the level on January 1, 1942, was about six times as high in Well US 108 as in Well US 68 (Fig. 2), but expressed as frequency-numbers, these two water-levels were nearly equivalent (Fig. 3). In other words, water-levels lower than those of January 1, 1942, are about equally common in both wells. On April 1, the water-levels in

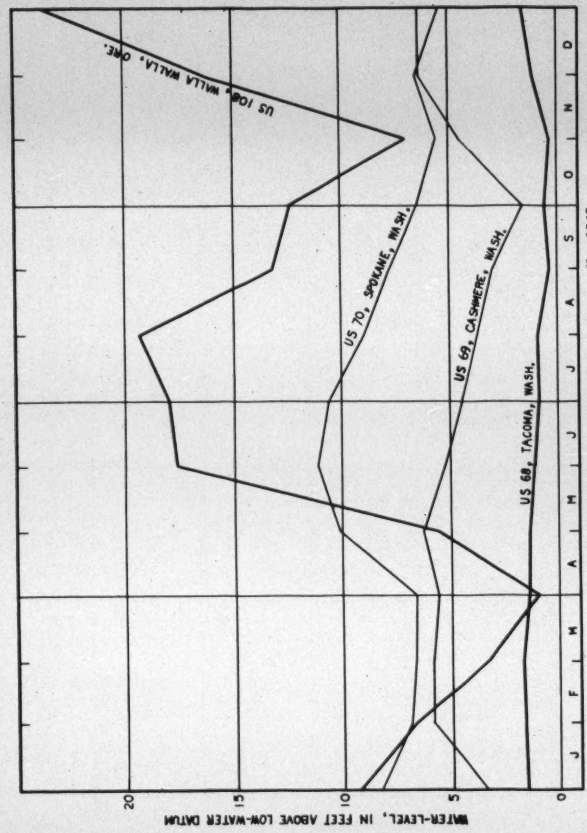

Fig. 2--Hydrographs of four observation-wells, 1942

both these wells were near the lowest of record, yet in terms of frequency of recurrence, this low level was much more uncommon for Well US 108 than for Well US 68. From March 1 to September 30, 1942, there was a net decline of water-level in wells 68, 69, and 70 but there was a net rise in Well US 108. This is shown by both Figures 2 and 3. The hydrographs in Figure 2 and data in Table 4, which follow, indicate that the rise in Well US 108 was 9.07 feet while the decline in Well US 68 was only 1.11 feet. However, this comparison does not fully evaluate the two water-level changes, because the corresponding increase and decrease in frequency-numbers are each about 22 per cent. In other words, water-levels have occurred within the 9.07-foot range in Well US 108 no more frequently than within the 1.11-foot range in Well US 68.

In any group of observation-wells, differences in the character of the water-bearing materials and in conditions of ground-water occurrence generally result in water-level hydrographs of different form. Hydrographs based upon frequency-numbers may evaluate the similarity between hydrologic conditions more readily than height-hydrographs. For example, in Figure 3, the graphs

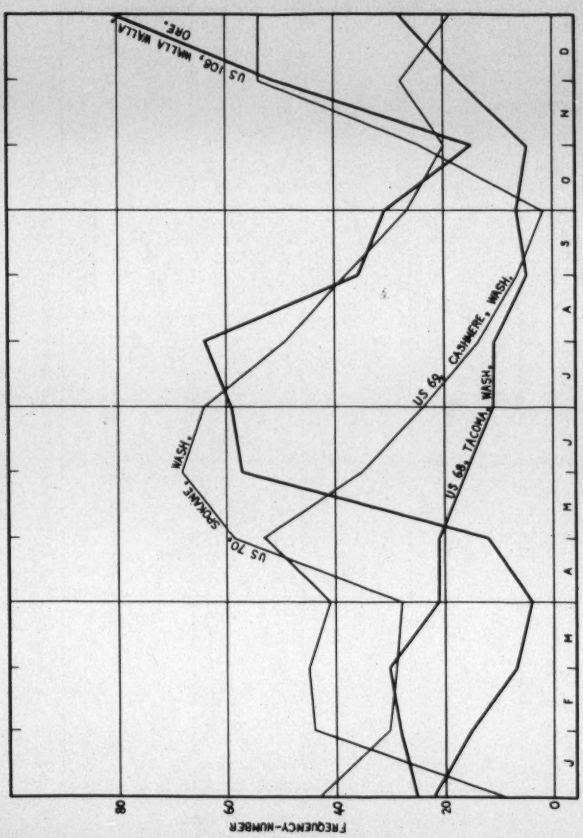

Fig. 3--Frequency-hydrographs of four observation-wells, 1942

for wells US 70 and US 108 are somewhat alike and those for wells US 68 and US 69 are also somewhat alike, but these two pairs of hydrographs are dissimilar in form. Accordingly, at least two distinct hydrologic regimens seem to be represented. The distinction is not nearly as evident from Figure 2. An alternative method for evaluating differences between observation-wells is used by MERRIAM [2], who tests each individual of a group of observation-wells by comparing water-levels in it with the average of the water-levels for the group.

For interpretative purposes, the water-levels in a group of observation-wells on a particular date may be averaged to determine the mean water-level for an area, or the water-level change during some interval of time may be similarly treated to derive a figure for the mean change. However, it is questionable whether the water-levels in all wells of the group respond equally to the same hydrologic forces and so whether all the levels should be given the same weight in determining the average. Some effects of indiscriminate averaging are indicated by Table 4, which

Table 4--Net water-level changes in four wells from March 1 to September 30, 1942

Wells and groups of wells	Rise (+) or decline (-) of water-level	Increase (+) or decrease (-) of frequency-number
	feet	pct
US 108, Walla Walla Basin, Oregon	+9.07	+22
US 70, Spokane, Washington	-0.29	- 2
US 69, Cashmere, Washington	-4.27	-43
US 68, Tacoma, Washington	-1.11	-23
Average, all four	+0.85	-12
Omitting US 108	-1.89	-23
Omitting US 70	+1.23	-15
Omitting US 69	+2.55	- 1
Omitting US 68	+1.50	- 8

gives the net water-level changes in the four wells from March 1 to September 30, 1942. The average of the changes in all four wells was a rise of 0.85 foot but the average of the corresponding changes in frequency-number was a decrease of 12 per cent. The 0.85-foot average rise must be a distorted value because, if the mean trend of water-levels had been upward, the corresponding average of frequency-numbers should have increased rather than decreased. The cause of the distorted average is evident--in comparison with the data for the other three wells, the rise in Well US 108 is large when expressed as distance in proportion to the increase of its frequency-number. In other words, the water-levels of this well have an inordinately large spread and inordinately influence every arithmetic average in which they are included. This is indicated in Table 4 by the averages that involve three of the four wells. In general, it may be concluded that a dependable arithmetic average may not result from a set of water-level data if the standard deviation of the water-levels in the several wells ranges widely.

As has been indicated, the average of water-levels in a group of wells may be adversely influenced by adding wells to or omitting wells from the group. This difficulty is caused in part by differences among the observation-wells in spread and in distance from mean water-level to the datum-plane. If measurements in a well must be discontinued, the method of frequency-analysis can be used to evaluate a substitute well soon after it has been established. Thus, the first few water-levels measured in the well are plotted on probability paper against the concurrent frequency values from one or more of the long-established wells. If the resulting points define a straight line on the probability-paper, that line is extended to determine tentative frequency-characteristics for the new well. Or, if the first measured water-levels are nearly alike, a tentative straight-line graph is drawn parallel to the graphs for adjacent long-established wells. Undoubtedly the accuracy of this procedure will vary considerably from well to well; the procedure probably would be acceptable if all the long-established observation-wells in the area have shown similar frequency-characteristics.

The greatest utility of the frequency-method herein treated may arise from the fact that the data are expressed in terms of conventional statistical measurements which are directly related to the whole background of probability-theory. This discussion has been concerned mainly with comparisons of water-levels or averages of water-levels; however, other uses of the method can be anticipated. A frequency-analysis of water-level data may be used to determine the optimum depth for constructing a well or the most advantageous setting for a centrifugal pump or other mechanical equipment that may be influenced adversely by water-level fluctuations. It is also possible that rainfall-data, river-discharge, and quantitative hydrologic data other than water-level records can be treated similarly to afford a means of correlation with water-level measurements in wells and a new method of predicting one from the other. As yet the possibilities of the method have been explored only superficially by the writer.

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APPLICATION OF THE SYNTHETIC UNIT-GRAPH IN THE WESTERN MOUNTAIN STATES

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Synopsis

In 1938 F. F SNYDER [see 1 of "References" at end of paper] presented a method for synthesizing unit-hydrographs for any basin from certain physical measurements of the basin. The writer has found the procedure to be a very convenient tool in the solution of many hydrologic problems for which approximate unit-hydrographs are necessary. The equations and constants presented by Snyder were developed from data for streams in the Appalachian Highlands. During the past year the writer, engaged in developing river-forecasting methods for the Sacramento and Lower San Joaquin rivers in California, has had occasion to note that some changes in the procedure are necessary before it can be applied to streams of that area. This paper presents the results of an investigation to determine the necessary adjustments for Snyder's methods in order to make them most effective for use in the basins of the Sierra Nevada and Coast Range. Although this investigation was conducted with the thought that Snyder's method could be adapted to meet the different conditions, the possibility that an entirely different approach might prove more satisfactory was not neglected. It developed that an adaptation of the original method gave only slightly less reliable results than did an entirely different, more complicated, and no more logical solution. It is felt that the simplification gained by adhering to the one procedure far outweighs the minor gain in accuracy through a major change in method.

Introduction

It is assumed that the reader is familiar with the general theory of the unit-hydrograph [2,3,4,5] and with the original paper by SNYDER [1]. The symbols used by Snyder will be adopted in this paper. They are:

t_p = "Basin lag", in hours
t_r = Unit of duration of surface-runoff producing rain, in hours [taken as $(t_p/5.5)$]
t_R = Length of surface-runoff producing rain, in hours
T = Time-base of the unit-hydrograph, in days
L = Length of area, in miles
L_{ca} = Distance from station to center of area, in miles
A = Drainage-area, in square miles
q_p = Peak-rate of discharge of unit-hydrograph, in cubic feet per second per square mile
Q_p = Peak-rate of discharge of unit-hydrograph, in cubic feet per second = (q_pA)
$C_t C_p$ = Coefficients depending on units and drainage-basin characteristics

The equations presented in the original paper are

$$t_p = C_t(L_{ca}L)^{0.3} \quad \text{where } C_t \text{ varied from 1.8 to 2.2} \tag{1}$$

$$q_p = (C_p 640/t_p) \quad \text{when } t_R = t_r,\ C_p \text{ varies from 0.56 to 0.69} \tag{2}$$

$$q_{pR} = C_p 640/[t_p + 1/4(t_R - t_r)] \tag{2a}$$

$$T = 3 + 3(t_p/24) \tag{3}$$

$$\text{Time to peak} = (t_p + 1/2\ t_r) \tag{4}$$

The data used in this report were collected from 18 basins in the Central Valley of California. The basins range widely in shape and topography, and in area from slightly over 100 square miles to about 3,700 square miles. The rainfall-distribution in basins draining from the Sierra Nevada and Coast Range is never uniform. Fortunately the pattern of rainfall-distribution is fixed to a large extent by orographic influences, and therefore the distribution-pattern in a given basin is reasonably similar in most storms, provided the basin is small enough so that variations in storm-path have little effect. Unit-hydrographs developed from actual stream-flow data reflect the characteristic rainfall-distribution of each basin. The synthetic hydrograph, averaging data from many basins, reflects only the general characteristic of higher rainfall at higher elevations, or, in other words, greater rainfall near the headwaters.

During the winter when the great bulk of the annual rainfall occurs, there is usually a heavy snow-pack in the higher mountains. This snow-pack reduces the area contributing to storm-runoff, and thus tends to cause shorter basin-lag and lower unit-hydrograph peak-flow than would be expected from the size and shape of a basin. In this paper runoff-volumes are assumed to be in terms of inches of depth over the entire basin. Flows in cubic feet per second per square mile are obtained by dividing flow in cubic feet per second by total basin-area. The basin-lag and unit-hydrograph peak-flows as determined represent the average effect of the reduction in area by the snow-pack.

The topography of the Sierra Nevada region is more rugged than that of the Appalachian Highlands. This tends to further reduce basin-lag from that which would be exhibited by otherwise similar basins in the Eastern States, and consequently results in increased peak-flows.

Method of solution

To conduct a satisfactory investigation of the unit-hydrograph characteristics of a basin, it is desirable to have records of stream-flow from recording river-gages and rainfall-data from one or more recording rain-gages. In the region under study recording rain-gage data are available from the records of the Weather Bureau's hydroclimatic network since about 1938. In many basins, river-gages have been installed at a still later date. It was found that the maximum value could be obtained from the scanty data by plotting two relations:

(a) Duration of rainfall against time from beginning of rain to hydrograph-peak (see Fig. 1)
(b) Duration of rainfall against unit-hydrograph peak-flow (see Fig. 2).

When data from all runoff-events are entered in these relations and curves are fitted to these data, the curves provide a means for fixing the time and height of the unit-hydrograph peak for storms of any duration. Thus the data from the events of complex storms, the small storms, and the storms of odd duration are combined to support the unit-graphs developed from hydrographs of isolated storm-events in the conventional manner.

The equations of the synthetic unit-hydrograph are the equations of these two relations. In fact, in lieu of the synthetic unit-graph, these curves can be used to develop unit-graphs for hydrologically similar basins.

Determination of basin-lag

Snyder defines basin-lag, t_p, as the time from center of mass of rainfall to the peak of the runoff-hydrograph. He assumes that basin-lag is a constant for any basin for a storm of given type. Assuming the center of mass of rainfall to be at the chronological mid-point of the storm, equation (4) gives the time to peak as equal to the lag plus half the duration of rain. This is the equation of a straight line with an intercept on the time-to-peak axis equal to t_p and a slope of one-half.

All curves of duration against time to peak (Fig. 1) for the California basins plotted as straight lines or nearly straight lines, but in no case was the slope equal to one-half. This invalidates the theory (for California basins at least) that basin-lag is a constant. In order to apply an equation similar to (1) to compute the lag it is therefore necessary to adopt a standard unit of duration. It was felt that the value of the intercept on the time-to-peak axis was the best for this purpose. The lag for a storm of very short duration, t_{pO}, was therefore correlated with the product ($L_{ca}L$). It was found that equation (1) could be applied if the constant C_t, was taken between 0.3 and 0.7. The average value of C_t was found to be 0.5.

The value of C_t for the California basins is approximately one-fourth as great as for streams

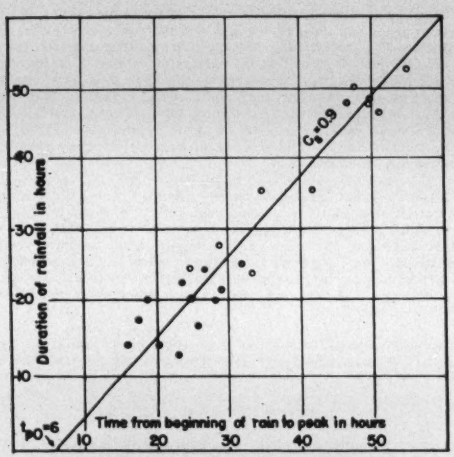

Fig. 1--Duration of rain versus time to peak, American River at Folsom, California

of the Appalachian area, with values of t_{pO} reduced in the same proportion. This would be anticipated from the general comments in the introduction.

Time to peak--Since the assumption of constant lag does not apply to the streams of the Central Valley, equation (4) must be altered to allow for a variable lag. It may be written in the general form

$$\text{Time to peak} = (t_{pO} + C_s t_R) \tag{4a}$$

C_s in this equation is the slope of the curve of duration against time to peak (Fig. 1). For the basins studied for this paper C_s varied from 0.7 to 1.0 with the average value being about 0.85. The more precipitous basins had in general the lower C_s-values, but no ready correlation with basin-slopes was apparent.

Although the value of C_s for the western basins is greater than the value of 0.5 determined by Snyder, the great reduction in t_{pO} results in generally shorter values of time to peak for durations up to about 36 hours.

Determination of basin-lag for any duration of rain

The computation of basin-lag, t_{pO}, for storms of very short or zero-duration has been discussed. Accepting Snyder's definition of lag as the time from center of mass of rainfall to hydrograph peak and assuming, as Snyder did, that the center of mass of rainfall is coincident with the mid-point of the duration, then

$$t_{pR} = \text{Time to peak} - 0.5t_R \tag{5}$$

where t_{pR} is the lag for a storm of duration t_R. Combining equations (4a) and (5)

$$\left.\begin{aligned} t_{pR} &= t_{pO} + C_s t_R - 0.5t_R \\ t_{pR} &= t_{pO} + (C_s - 0.5)t_R \end{aligned}\right\} \tag{5a}$$

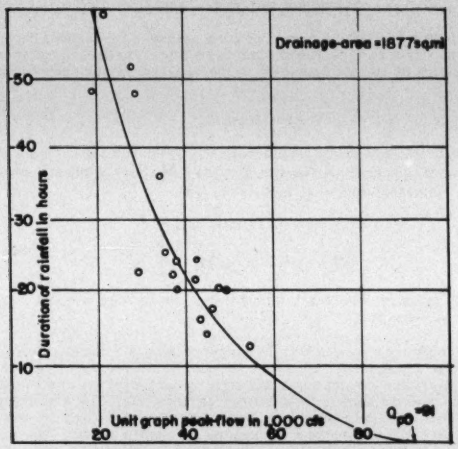

Fig. 2--Duration of rain versus unit-graph peak-flow, American River at Folsom, California

Determination of peak-flow of unit-hydrograph

The peak-rate of flow of the unit-hydrograph, Q_p, is equal to q_pA. Snyder determines q_p by means of equation (2) for storms of unit-duration, which he takes as $(t_p/5.5)$. In this study t_{pO} has been found to be approximately one-fourth that determined by Snyder, and t_r is therefore reduced in equal proportion. For western basins as large as 4,000 square miles, t_r will rarely exceed two hours.

The variation of unit peak-flow with duration is a hyperbolic function [equation (2a) and Fig. 2]. It is difficult to determine values of unit-hydrograph peak-flow for storms of very short duration since few data are available to fix the location of the lower portion of the curve of Figure 2. To determine values of C_p empirically it is necessary to work with storms of longer duration than t_r as defined by Snyder.

One approach would be to accept Snyder's equation (2a), substitute observed data and solve for C_p. Since Snyder assumed t_p was a basin-constant for any type of storm, he was forced to introduce the term $[1/4\ (t_R - t_r)]$ into the denominator of equation (2a) in order to allow for the observed reduction of unit-hydrograph peak-flow with increased duration of rain. If equation (5a) is compared with the denominator of equation (2a), considerable similarity will be noted. If C_s is taken as 0.85 the term $(C_s - 0.5)t_R$ becomes $0.35\ t_R$ [equation (5a)], while in the denominator of equation (2a), if t_r is small the term $[1/4\ (t_R - t_r)]$ approaches $0.25t_R$. This similarity leads to the assumption that equation (2) written in the general form

$$q_{pR} = (C_p 640/t_{pR}) \qquad (2b)$$

will serve to define q_{pR} for any duration of rain. By substituting actual data in equation (2b) this assumption was found to be valid. The coefficient C_p appears to vary from 0.35 to 0.50, and to average 0.42 for the California basins.

It is interesting to note that since equation (2a) is the equation of a hyperbola becoming asymptotic to the duration of rain-axis, values of q_{pR} approach equality as duration increases. This condition is even more marked when equation (2b) is used, since t_{pO} is small and t_{pR} is largely dependent on duration of rain.

Length of unit-graph base

The time-base of a unit-hydrograph developed from stream-flow records depends largely on the procedure used to separate surface-runoff from base-flow. The writer has therefore made no change in Snyder's equation (3) for the time-base of the unit-hydrograph except to write it in the general form

$$T = 3 + 3(t_{pR}/24) \tag{3b}$$

Since t_{pR} varies with the duration of rain [equation (5a)] the computed values of T will likewise vary with duration. Neglecting t_{pO} and taking C_s as 0.85 then t_{pR} equals approximately 0.35 t_R [equation (5a)]. Inserting this value in equation (3a)

$$\left.\begin{aligned} T &= 3 + [3\ (0.35t_R)/24] \\ T &= 3 + [1.05\ t_R/24] \end{aligned}\right\} \tag{3b}$$

Remembering that t_R is in hours, whereas T is in days, it can be seen that any increase in t_R results in a nearly equal increase in T.

The unit-hydrograph theory assumes that the length of base is a constant for all storms of the same duration regardless of magnitude. Since the equation of the recession side of the hydrograph [6] takes the form $Q = Q_0k^t$, this assumption is not strictly correct. The time required for the recession evidently varies with the magnitude of the hydrograph-peak. The writer has on occasion found it necessary to define only the rising limb, time and height of the hydrograph-peak by the unit-hydrograph, and then to determine the recession by means of a stream-flow recession-curve.

Adhering to the assumption of a constant time for the recession it is still reasonable to vary the length of base with duration of rain. The time-base of the unit-graph is equal to the duration of rise plus the duration of the recession. With the latter element a constant and the duration of rise varying with length of rain [equations (4) and (4a)], then the length of base must also vary with the duration of rain.

Distribution of runoff

Figure 2 of the original paper presents distribution-percentages for any basin as a function of basin-lag. Since lag and length of base were assumed constant for a given basin, the distribution-percentages obtained by Snyder were also constant. The curves seem to work quite satisfactorily for California streams if t_{pR} [equation (5a)] is used for the abscissae. This results in varying distribution-percentages with variations in duration of rainfall.

Table 1--Comparison of synthetic unit-graph formulas

Appalachian Highlands	Northwestern States
Basin lag	
$t_p = C_t(L_{ca}L)^{0.3}$	$t_{p0} = C_t(L_{ca}L)^{0.3}$
C_t varies from 1.8 to 2.2	C_t varies from 0.3 to 0.7
	$t_{pR} = t_{p0} + (C_s - 0.5)t_R$
	C_s varies from 0.7 to 1.0
Time to peak	
$t_p + (1/2)t_R$	$t_{pR} + (1/2)t_R$
	$t_{p0} + C_st_R$
Unit-hydrograph peak-flow	
$q_p = C_p640/t_p$ when $t_R = t_r = t_p/5.5$	$q_{p0} = C_p640/t_{p0}$
C_p varies from 0.56 to 0.69	C_p varies from 0.35 to 0.50
$q_{pR} = C_p640/[t_p + 1/4(t_R - t_r)]$	$q_{pR} = C_p640/t_{pR}$
$Q_{pR} = q_{pR}A$	$Q_{pR} = q_{pR}A$
Time-base of the unit-graph	
$T = 3 + (3t_p/24)$	$T = 3 + (3t_{pR}/24)$

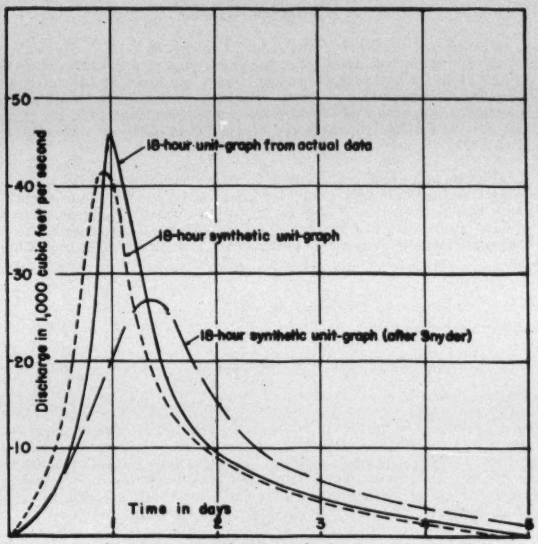

Fig. 3--Comparison of unit-graphs for American River above Folsom, California

Conclusion

Table 1 summarizes the results of this study and presents a comparison with the results of Snyder's study in the Appalachian Highlands. His concluding comments apply equally well in this case. Figure 3 shows a comparison between unit-hydrographs determined in various ways for the American River at Folsom, California.

Although the data used in this paper were drawn entirely from northern California streams, it is believed that the similarity of conditions in a large part of the northwestern United States should make the procedures generally applicable to that area. The writer feels that similar studies conducted in other parts of the country would eventually result in the determination of appropriate constants for all regions and thus make the synthetic unit-graph procedure more universally useful than it is at the present time.

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U. S. Weather Bureau,
Sacramento, California

DISCUSSION

FRANKLIN F. SNYDER (Office, Chief of Engineers, Washington, D. C.)--The writer was extremely interested in studying the results of the author's analysis of unit-hydrographs and possible methods of synthesizing them for basins of the Sierra Nevada and Coast Range in California. A variation in the coefficients developed by the writer for the Appalachian Highlands was to be expected, and the important items, so far as checking the general applicability of the original procedure is concerned, are the verification of the exponent of 0.3 in equation (1) and the hyperbolic relationship of equation (2).

Since the original paper was presented, another study has been made by the writer using the synthetic unit-graph procedure [F. F. SNYDER, Predicting headwater river-stage directly from rainfall, Trans. Amer. Geophys. Union, pp. 485-490, 1940]. An equation presented in that paper should be added to those presented in the original paper by the writer and repeated for reference by the author. This equation empirically defines the variation of lag with duration of effective rainfall as follows

$$t_{pR} = t_p + (t_R - t_r)/4 \qquad (1a)$$

Equation (2a) could then be written

$$q_{pR} = C_p\, 640/t_{pR} \qquad (2a)$$

which is presented by the author in equation (2b).

The relationships presented by the author in Figures 1 and 2 are instructive and can be developed from storms of any duration. However, in addition to the requirement of a characteristic basin-rainfall distribution as discussed by the writer, a special requirement as to fairly constant rainfall-intensity would appear to be necessary to obtain a useful relationship as illustrated in Figure 1. One of the principal advantages in using the unit-hydrograph procedure in most regions is the manner in which it enables one to handle varying rates of rainfall.

As indicated previously, the original assumption of a constant lag was revised [see reference above] and consequently the equation for the time from beginning of runoff to the peak-discharge for the general case is

$$t_{pR} + t_R/2 = t_p + (t_R - t_r)/4 + t_R/2 = t_p + (3t_R - t_r)/4$$

and since $(t_r/4)$ by definition is $(t_p/22)$

$$\text{Time to peak} = (21/22)\, t_p + 0.75\, t_R \qquad (4a')$$

As would be expected, a comparison of equation (4a') with equation (4a) presented by the author indicates that the value of C_s is practically the same for the Appalachian and northern California areas. However, if the rainfall-intensity is not fairly constant, a weighted value of t_R must be used and if bursts of heavy rainfall are separated by a time-interval approaching a value approximately as large as the basin-lag, better results are obtained by treating them as separate-storm experiences.

The author's values of t_{pO} and Q_{pO} are not directly comparable to values of t_p and Q_p. It is believed that t_{pO} and Q_{pO} as obtained from Figures 1 and 2 are imaginary quantities, and their values would not be realized in nature even if an instantaneous application of rainfall occurred. The selection in the original paper of a value of $t_r = (t_p/5.5)$ was designed to make the unit of time equal to that minimum value below which a further decrease would have little or no effect on either the basin-lag or unit-hydrograph peak-discharge. This hypothesis is based on the time-contour concept of runoff. The zone contributing the peak-flow (zone with maximum width) past a gaging-station has a definite length (in time), and a decrease in the unit of rainfall-duration, t_r, below this duration has little or no effect on the lag or peak-flow of unit-hydrographs. The average value of the time-length of this zone in the original study for the Appalachian Highlands was based on the inspection of a number of area-shaped diagrams and mass-curves of drainage-area against distance from the gaging-station, and the value of t_r was empirically fixed at $(t_p/5.5)$.

The 18-hour synthetic unit-graph labeled (after Snyder) on Figure 3 might be better identified as based on Appalachian Highlands data. It was never intended that the variable coefficients, C_t and C_p, developed for one area be used for areas other than those of like hydrologic characteristics.

It can not be stressed too emphatically that the value of basin-lag should not be computed whenever it can be obtained by observation. It can be obtained at very little expense, since a few field-observations of time of cresting of the stream are all that is required in most cases. Of course, if there are no existing rainfall-stations in or near the basin, special arrangements would also have to be made to obtain data on the rainfall.

With respect to the comparison of coefficients for the Appalachian Highlands and northern California given in Table 1, it is believed that the indicated variation between the two regions is greater than actually exists.

The writer has seen the result of studies applying the procedure to drainage-basins in all sections of the country including the Rocky Mountains and southern California, and has never seen a case where the value of C_t was less than 0.5. Partial explanation of the low value of C_t (0.3 to 0.7) obtained by the author is due to the fact that t_{pO} is a smaller quantity than t_p thus requiring a smaller value of C_t. Another reason, as pointed out by the author, is the use of physical measurements of the whole basin when snow is restricting the runoff from the higher elevations. It would appear that a more successful course for forecasting usage would be to eliminate the zones of minor contribution and develop coefficients for the actual area involved. Flood-peaks and the times of their occurrence could then be computed on a basis of conditions existing at the time the storms occurred.

The range in values of C_p from 0.35 to 0.50 for California as compared to a range of 0.56 to 0.69 for the Appalachian Highlands is not so easily understood. Drainage-basins with a small value of C_t usually have a large value of C_p. The fact that the quantity t_{pO} is smaller than t_p partially explains the difference. The possibility that some snow-melt has been included in the runoff might suggest smaller values for the unit-hydrograph peaks, but would also call for larger values of lag unless the snow-melt is usually confined to zones having little or no effect on the peak-discharge.

The author has contributed some valuable relationships between duration of rainfall and time of peaking, and between duration of rainfall and unit-hydrograph peak-discharge. The information presented concerning the coefficients C_t and C_p for California should be of considerable assistance to anyone engaged in studying the runoff-characteristics of areas similar to those covered by the study.

ON THE USE OF A RADIOACTIVE-TRACER METHOD IN MEASUREMENTS OF WATER

V. F. Hess

Introduction--In spite of the great variety of known methods for measuring the flow of water, there are situations in which for one reason or another all of them fail to offer the hydraulic engineer, or the hydrologist, a satisfactory solution. Specifically, there are limitations as to the amounts of water that can be diverted for direct measurement either by volume or by weight; space and the necessary head may not permit the use of a weir; shortness of the water-passage and lack of sufficiently simple geometric form may preclude measurement by water-hammer (Gibson method) or by salt velocity (Allen method); while turbulence may make measurements by current-meter or by pitot-tube entirely unreliable. In some cases even a measuring section of readily determinable area cannot be found, as for example in underground channels. Consequently, for many years the measurement of large volumes of water used by low-head hydroelectric plants has been a difficult but most important problem.

To meet this situation B. F. GROAT [see 1 of "References" at end of paper] proposed the use of salt as a tracer and actually tested with some success water-wheels using as much as 3,000 cubic feet of water per second.

The principle is very simple: A strong solution of salt is distributed throughout an unknown flow of water, Q, by being fed at a constant and readily determined rate of q cubic feet per second. After allowing a sufficient mixing time, tail-samples were withdrawn from a point downstream. By titration the ratio, R, between the original strength of the solution and the concentration in the tail-samples could be determined, and thence it followed that

$$Q = qR$$

This method had one principal objection--the enormous amount of salt necessary to secure sufficient concentration in the tail-samples to permit accurate and reliable analysis by titration. To overcome this JOLY [2] suggested the use of radium, but as far as is known no experimental results have ever been published which demonstrate the practicability of Joly's method or the limitations to which it might be subject. It is interesting to note that Joly estimated that to measure flows of 10,000 liters per second, or approximately 350 cfs, it would require but 0.064 mgm of radium at a cost of 36 shillings. He assumed the injection-time to be 20 minutes and the concentration in the tail-samples to be 5×10^{-15} gm per cc in order that he might obtain an accuracy of one per cent.

If we translate Joly's estimates to the scale of tests attempted by Groat we find that for a single run of ten minutes it would be necessary to use only 0.25 mgm of radium costing at present about $6. For a complete test, possibly 20 points would suffice so that the total cost of the radium would be but $120, which would be small compared with the outlay for tests of this nature. For an actual test of a large water-wheel the cost exceeded $5,000, but a single unexpected by-product permitted the owner to make a saving of $50,000.

It thus appears that if Joly's estimates can be substantiated, the possibilities for measuring flows of considerable magnitude by radium instead of salt would be very attractive. It was the author's purpose to investigate thoroughly any limitations or difficulties which Joly had apparently not anticipated, as it was feared that spurious precipitations of radium, the natural radium content of river water, contamination of the samples, etc., might introduce complications which would make it necessary to increase materially the amount of radium used in order to secure reliable analyses of the tail-samples.

Opportunity for experimentation--An ideal opportunity for investigating this problem was afforded by the fact that the Pennsylvania Water and Power Company placed at my disposal a large weighing-tank having a capacity of about 17 tons (575 cubic feet) located at their steam-plant on the Susquehanna River. In this way it was possible to study the disturbing influences which might arise in actual testing with flowing water, but at the same time to be entirely free from uncertainties resulting from imperfect mixing or errors in determining either the rate of injection or even the quantity of flow necessary to check the results by independent means. For the purpose at hand still water serves just as well as flowing since the essence of the problem in either case is simply the determination of the ratio of concentration of two solutions before and after mixing. In many of the tests I was not given the weight of water in the tank until my work was completed, and then I was afforded a check of unquestioned accuracy by the most precise means known for measuring water--actual weight.

Anticipated difficulties--The difficulties which can be expected with dilutions of solutions of radium with ordinary river-water are, of course, mainly spurious precipitations of radium, presumably as $RaSO_4$ by traces of SO_4-ions in the water. $RaSO_4$ is almost insoluble in water; a deposit of radium as a sulfate gives off much less radon and, therefore, any method based on the measurement of radon in water then would indicate an apparent loss of radium in the solution. The effect of this loss would be to overestimate the amount of water in the tank and, therefore, plus errors would indicate losses of radium to be prevented or controlled by whatever means might be found for arresting these precipitations.

At the time this program was begun consideration was given to the use of radiophosphorous and other artificially radioactive materials, but under the conditions at that time it was found after a few experiments that it would be best to confine the scope to radium alone.

Method--The method followed is substantially that tail-samples were returned to the laboratory for de-emanation after a period of a number of days while the radon accumulates. At the end of this time the radon was washed by passing dry filtered radon-free nitrogen through the solution in order to transfer it to an ionization-chamber where the radioactivity could be measured in the usual manner.

For the ionization-measurements a differential method was employed which had been developed previously for various purposes by my coworkers [3].

The main advantage of this method is the elimination of the disturbing influence of changes in the intensity of cosmic radiation since both chambers being identical are influenced equally, except in the very rare case of "unidirectional" bursts.

The apparatus (Fig. 1) consists of two large cylindrical ionization-chambers having a volume

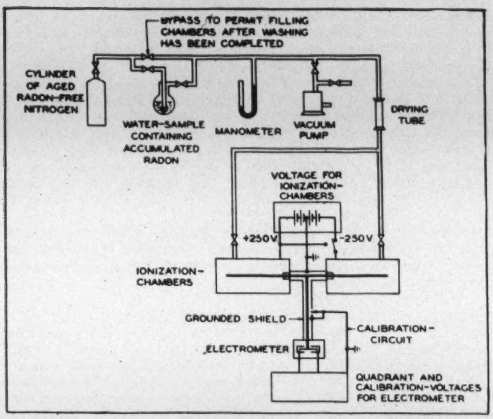

Fig. 1--Schematic diagram, apparatus for measurements of emanation

of one cubic foot each. The inner electrodes of the chambers, both provided with a guard-ring system, are connected with a Lindemann electrometer [4] of medium sensitivity--50 scale-divisions per volt. The outer walls of the chambers are connected with a battery and kept at +250 and -250 volts, respectively. The needle of the electrometer when disconnected from ground will stay at its zero-position if both chambers are equally ionized. If, for instance, the left chamber is evacuated and then some radon is introduced into it from a solution, the fiber of the electrometer begins to migrate. The rate of drift of the fiber (at the time when radioactive equilibrium is reached) is a measure of the amount of radon in the chamber.

This double ionization-chamber apparatus was constructed and set up at Fordham University, by collaboration of F. A. BENEDETTO, S.J., in the winter of 1940-41.

A Cenco Hyvac pump with connections to both chambers, a large drying tube of phosphorous pentoxide, a full-length mercury-manometer, a side connection with a nitrogen tank through a Hoke needle-valve, filters of steel wool and cotton, etc., permit evacuating or filling the chambers to any desired pressure with filtered and aged (radon-free) nitrogen. All connections are made through glass tube and glass stop-cocks with short stout pieces of vacuum hose. Evacuation of the whole apparatus with one of the chambers takes about 15 minutes.

When both chambers are filled with inactive nitrogen, the ionization of both chambers is nearly the same--the needle, therefore, drifts very slowly. In the ideal case of complete compensation saturation-currents in the right and left chambers (i_L, i_R) are equal. If the compensation is not quite perfect, a small differential current $i_D = (i_L - i_R)$ is observed. If in a subsequent experiment both chambers are kept at the same potential, for instance, both positive, the drift of the needle indicates the sum of the two currents, $i_S = (i_L + i_R)$. From the two equations for i_D and i_S, the ionization-currents in the two individual chambers can be obtained.

In order to measure the quantity of radon accumulated in a radium-solution over a given time, one of the two chambers is completely evacuated. Then nitrogen is sent in a steady stream through the washing-bottle containing the solution into the chamber, after passing through a filter of steel wool and a drying tube. This "bubbling" process is continued for 15 to 20 minutes. The nitrogen bubbling violently through the solution removes the radon completely. Experiments showed that even two or three washing-bottles each containing about 800 cc of solution could be de-emanated in 20 minutes of bubbling. These bottles were so connected in series that the nitrogen gas passed through them successively. By the end of this bubbling-time the chamber has been usually filled to about half the atmospheric pressure. Then the by-pass stop-cock is opened and the filling of the chamber with nitrogen from the tank is completed.

The radon is then kept in the chamber until equilibrium with its successive products radium A to radium C is reached, about 3-1/2 hours after filling. It is important to keep the voltage on the chamber during this period. Then the actual measurements are begun. Usually 25 single runs through 20 scale-divisions visually observed and timed with a stop-watch, are sufficient to give a reliable mean value of the ionization-current. The large fluctuations of the times of each individual drift through 20 scale-divisions are mainly due to the natural statistical fluctuations in the alpha-ray emission. With a sensitivity of about 50 scale-divisions per volt, and a total capacitance of the apparatus of 34.4 cm, the average number of alpha rays emitted during a drift of 20 scale-divisions is 600; from this we can expect a mean fluctuation of (1/600) = 0.04 or ± 4 per cent. Individual runs, therefore, may differ by eight per cent or more. If 25 runs are summed up as a general mean value, the accuracy of this would be about ± 0.8 per cent, from the statistical point of view.

Mesotron-showers in cosmic radiation may in some rare cases influence the ionization of one of the two chambers more than the other. This would tend to increase slightly the margin of statistical error, stated above. Such fluctuations could, however, be recognized as such and the readings then need not be included in the average.

Twenty-five single runs of 20 scale-divisions require about one hour. After this the apparatus is evacuated and refilled with inactive nitrogen. It can be used again a few hours afterwards, when the radioactive deposit has decayed completely. The natural "zero"-run (when both chambers are filled with inactive nitrogen) usually corresponds to 20 scale-divisions in 200 minutes while with radon the drift-time in our experiments is of the order of two minutes. Thus the differential method always provides a fairly low ratio of the differential "background-ionization" current as compared with the current due to radon in the chamber, about 1:100. Changes in the differential background-current, i_D, of even 50 per cent are harmless because they amount to only 0.5 per cent of the main current to be measured.

To calibrate the apparatus a number of experiments with a 10^{-11} gram radium-solution of the National Bureau of Standards were performed. The mean value of the saturation-current corresponding to one curie of radon was found to be 4.53×10^7 volts/sec or 5.2×10^6 ESU if we take the capacitance of both chambers together with the Lindemann electrometer as 34.4 cm. Naturally this value includes also the ionization from the alpha rays of radium A and radium C. Calibration of the capacitance of the apparatus was carried out twice with two different standard-condensers (one Wulf condenser and one Gerdien variable condenser) kindly lent by the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, D. C. The two calibrations gave 34.6 and 34.2 cm, respectively.

Procedure--The procedure when reduced to simplest terms is essentially the determination of concentration of two solutions differing widely in strength. In the tank-experiments about two pounds of strong or head-solution is mixed with about 34,000 pounds of river-water so that the resulting tail-sample is diluted approximately 15,000 times. No single means of measuring radioactivity can be expected to maintain a satisfactory degree of accuracy over such a tremendous range of values, so in order to use the same apparatus for both determinations, and in this way eliminate errors resulting from inaccuracy of calibration, a small sample of the head-solution is diluted in steps of about 100 times to approximately the same strength as that of the tail-samples. This work has to be carried out with care comparable to that required in bacteriology to insure reliable results. Table 1 indicates the order of variation that was found in separate determinations of the strength of the head-solutions as it was sent to the field for dilution with river-water.

Table 1--Results of measurements on independently prepared head-solution samples

(A)	(B)	(C)
0.683×10^{-6}	0.715×10^{-6}	5.220×10^{-11}
0.714×10^{-6}	0.695×10^{-6}	5.170×10^{-11}
0.689×10^{-6}	0.715×10^{-6}	5.230×10^{-11}
0.719×10^{-6}		5.280×10^{-11}
0.700×10^{-6}		5.219×10^{-11}

In addition to the dilution-experiments made with distilled water, Susquehanna River water was shipped to the laboratory to see whether harmful precipitation would take place. By allowing the diluted solution to stand for several weeks it was clearly shown that losses of ten to 20 per cent in radioactivity were observed. Various chemicals and acids were tried to counteract or to slow up this process, the most successful of which was HCl in small amounts (about 30 cc/liter).

Table 2--Summary of Holtwood weighing-tank experiments with radium-solutions in approximately 34,000 pounds of water (544 cubic feet)

Number and date	Deviation from mean individual tail-samples	Error weight water-average all samples	Radium-concentration in tank-water, 10^{-14} gm Ra per gm H_2O	Product[a], [(4) × (3)]	Remarks
(1)	(2)	(3)	(4)	(5)	(6)
1941	pct	pct			
1 Mar. 12	0	+15.6	21	328	Initial test without special precautions
	- 0.9				
	- 1.5				
	+ 2.5				
2 May 8	.....	+ 5	Approx. 40	200	Radium-concentration doubled
3 May 12	.....	- 0.25	Approx. 40	10	30 pounds hydrochloric acid added directly to water in tank
4 June 26	- 2.6	+13	43	559	No acid added
	+ 2.6				
	+ 1.6	+ 0.6		26	Acid added to tail-samples before returning to laboratory
	- 1.6				
5 July 30	+ 4.0	- 1.3	48	62	Test for uniformity of mixing of radium-solution in tank by withdrawing samples from fixed locations instead of sampling method of other tests
	+ 0.5				
	- 5.7				
	+ 1.3				
	- 6.5				
	+ 6.5				
6 Oct. 14	+ 2.8	+ 9	40	360	Substituted nitric acid for hydrochloric in this test only
	- 3.0				
	+ 0.7				
	+ 6.3				
	+ 5.5				
	-12.4				
7 Nov. 13	+ 0.6	- 0.97	40	39	Used large amount of tail-samples to test reproductibility of results
	- 0.8				
	- 0.5				
	0				
	+ 1.5				
	- 1.0				
	+ 0.6				
	- 0.4				
1942					
8 Feb. 4	+ 0.25	- 0.2	8.1	2	Marked reduction in radium-content; emanation from two samples measured simultaneously to reduce laboratory work
	+ 0.5				
	- 0.7				
	- 0.04				
9 Mar. 6	- 0.2	-10.4	2.8	29	Still further reduction in radium-content; three samples measured simultaneously
	+ 0.2				
	0.0				
10 Apr. 7	- 1.2	- 1.1	3.7	4	Increased radium-content and added precautions to avoid contamination of samples; results corrected for natural radium-content of river-water
	+ 1.4				
	- 0.2				
11 May 6	- 1.6	- 2.8	4.0	11	For this and succeeding tests weight of water in tank was not revealed until after radium-measurements
	- 0.2				
	+ 1.8				

[a]This column is a measure of relative success since the difficulty of improving accuracy varies inversely with the radium-concentration.

Table 2--Summary of Holtwood weighing-tank experiments with radium-solutions in approximately 34,000 pounds of water (544 cubic-feet)--Concluded

Number and date	Deviation from mean individual tail-samples	Error weight water-average all samples	Radium-concentration in tank-water 10^{-14} gm Ra per gm H_2O	Product[a], [(4) × (3)]	Remarks
(1)	(2)	(3)	(4)	(5)	(6)
1942	pct	pct			
12 June 19[b]	- 2.4 + 2.4	+ 1.8	4.5	8	Differential method used by which effect of radium initially in the river-water was eliminated
13 July 24	- 0.1 + 0.7 - 0.6	- 1.9	4.7	9	Repetition of previous test
14 Sep. 1	+ 4.6[c] + 2.0 - 6.6	+15.1	2.0	30	Test at very low radium-content; abandoned differential method; measurements made during humid weather were unreliable due to insulator leakage
15 Oct. 9	- 1.5 + 0.8 + 0.7	+ 4.0	2.3	9	Repetition of above under favorable conditions
16 Feb. 24	- 0.2 - 0.3 + 0.5	+ 3.1	5.1	16	Previous experiments having shown errors due to apparent loss of radium, two tank experiments were run in quick succession to determine if error in one measurement might be used to correct error in second
	+ 4.6 - 2.7 - 1.9	+ 2.5[d]	4.4	36	

[b]Determination from one set discarded; deviation of -9.2 per cent.
[c]Only first determination used in calculation of water-quantity.
[d]As corrected by error in first part of experiment; as measured +5.7 per cent.

In the tank-tests the dilution was carried out in one step but instead of being dependent upon volumetric measurements the amount of the sample of head-solution and the water in the tank could be determined directly by weight. Table 2 shows the results that were obtained in the 16 tests together with notes regarding the variations in technique used in reducing the influence of disturbing factors. The percentage of error itself is hardly a true measure of success in this respect since the effect of uncontrolled sources is increased inversely with the strength of the tail-samples. Consequently in the last column the product of the error and the strength is given to indicate in relative terms the progress that was made during the course of this program.

Conclusion--Looking back over these experiments it is obvious that many disturbing elements are still not completely understood, although their effect has certainly been minimized by treating the water with dilute acid and taking into account the natural radium-content of the river-water itself. It should be noted that in each case where particularly bad results were obtained, some means were found which led to at least partial correction. It has been found that extreme care must be exercised regarding cleanliness of the glassware and that ordinary soft-glass bottles cannot be used.

There is little expectation of obtaining precise measurements unless the concentration of the tail-samples is kept well above that suggested by Joly. These experiments have been useful, however, in evaluating the difficulties that may arise so that in planning further work the experimenter will have a better idea of the practical limitations, and not attempt blindly to set out to measure large volumes of water with too little radium.

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DISCUSSION

L. F. CURTISS (National Bureau of Standards, Washington, D. C.)--I am glad to have an opportunity to congratulate Doctor Hess on a bold approach to a difficult problem. It is not surprising that the method of radioactive tracers should be applied to the study of the flow of natural waters when we consider that since the advent of artificial radioactivity the method has been used in fields as diverse as the manufacture of steel and the chemical reactions in the human body. The use of artificially radioactive tracers permits a choice of an element chemically suitable to the problem.

I would like to point out a difficulty in the use of radium to measure quantitatively the flow of natural waters which was not particularly stressed by the author in connection with his experiments in a large tank. He points out that considerable care must be taken to keep radium in solution even in the laboratory. The type of glassware, for example, must be selected with caution for use in storing solutions of radium, which must be kept in as pure a state as possible. This arises from the fact that radium sulphate is quite insoluble in water and may therefore be lost to measurement in terms of radon, when impurities are introduced into the solution. The author succeeds in obviating this difficulty in connection with his experiments in a large tank of water by adding hydrochloric acid to the sample after removing it from the tank or by adding the acid to the water in the tank before adding the radium. In actual measurements of river-flow neither procedure would be practicable. Sufficient acid could not be added to a stream to produce the desired result. Adding acid to a sample would not serve to recover radium already lost by precipitation in the stream.

In conclusion, I would like to say that the author has done well to call attention to the precautions which must be taken in applying this means of studying flow of water. It is my opinion that the difficulties may perhaps be overcome so that measurements of this type can be made successfully. If so, the method, as the author indicates, offers a very sensitive and inexpensive means of obtaining data almost impossible to obtain otherwise.

V. F. HESS--The use of artificial radioactive material as tracers is very limited on account of the short-life period of most of these elements. This in turn limits a choice of a chemically suitable element for the particular purpose in question. Furthermore, radiosodium, radiophosphorus, and other artificial radioactive material is available only in a few laboratories and in quantities not sufficient for large-scale experiments on water. Also, the use of beta-ray counters in connection with the problem of activated flowing water is very difficult, especially if an accurate comparison of samples under varying conditions is required.

Dr. Curtiss' remark on the impossibility of using large quantities of acid mixed with radium in flowing river-water, of course, is quite correct. In experiments with turbines, however, the time of contact of the weak radium-solution with the dirty river-water would be extremely short (a few minutes at most) because the samples taken at the point of outflow of the turbine could be acidulated with HCl immediately after taking them. I found that acidulated river-water samples keep fairly well since the process of deposition of radium by SO_4-ions takes many days, in the presence of an excess of H- and Cl-ions.

DEAN B. COWIE (Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, D. C.; communicated May 26, 1943)--The report by Dr. Hess on the measurement of large volumes of water by use of a radium-tracer technique is very interesting. It should stimulate the practical hydrologic engineer to a serious consideration of this technique for solutions of some of his most difficult problems--problems perhaps impossible with any other technique. However, with the use of certain of the artificial radioactive isotopes an even more sensitive method exists without the inherent difficulties encountered in the use of radium and its decay-products.

An examination of a few of these difficulties encountered in the use of radium as outlined by the author and a comparison of these procedures with artificial radioactive isotope methods illustrate this idea. The use of radioactive sodium for flow-measurements of large volumes of water has already been made. The choice of sodium is dependent upon its large yield from the cyclotron

and the extremely high energy of the emitted particles rendering this isotope extremely useful in such problems.

The measurement of the rate of flow by tracer-method requires an equilibrium-state of the tracer and the solution to be measured. If the tracer is not completely mixed with that quantity of solution being measured, erroneous results will then be observed. Both the radium-radon method and the artificial radioactive isotope method require this equilibrium. However, the procedure employed by the author requires: (a) An additional equilibrium of radium and its first decay-product radon; (b) a complete separation and withdrawal from the solution of all of the radon; (c) an accurate measurement of this radon to be correlated with final radium-concentration in the solution.

The complete equilibrium of radium-radon in solutions requires sealing in an air-tight system for 28 days or more unless additional considerations are made as to the state of equilibrium of the radon with its parent, radium. Three or four days must pass, however, before any measurement can be made even with such additional considerations. Where quick results are desired, radioactive sodium can be used when a detector such as a Geiger counter properly insulated is immersed immediately into the sample to be measured. A few minutes may then suffice for a single measurement where otherwise four days would have to pass before a measurement should be made.

A withdrawal of the radon from the solution also introduces difficulties not encountered in the artificial radioactive isotope method. Care in the choice of the glassware, the pH of the solution, and elimination of the SO_4-radical are quite important. The complete removal of radon from liquids can not be obtained by passing through the solution a stream of gas. Boiling the solution, however, will complete this removal. The solution must be acidic or else radium sulphate will be precipitated as an insoluble deposit on the walls of the vessel. Even in an acid solution colloidal particles exist which serve to act as further sources of adsorption of the radium. This adsorption on the walls of the vessel or on the colloidal material in the solution serve to introduce considerable errors. The proper choice of an artificial radioactive isotope eliminates all of these difficulties, as well as speeding up the time of measurement, since the chemistry involved in the use of a sodium-chloride solution, for example, is simple and straightforward.

The relative cost of the two methods again indicates the practicality of the use of the artificial radioactive isotope method. A gram of radium will cost about $25,000; a gram-equivalent of radioactive sodium would be of the order of several hundred dollars.

The final measurement of any sample of radon requires still further equilibrium. In less than three hours after radium is introduced into a closed ionization-chamber radioactive equilibrium is established between radon and its decay-products down to the long-lived radium D. Two of these products emit alpha particles which cause the ionization-current to increase as these products accumulate. This ionization-current is a maximum and practically steady from two hours and twenty minutes to about five hours and twenty minutes after the radon is admitted to the chamber. After this time it decreases according to the decay-rate of radon. The time involved in ascertaining this initial variation of ionization is not encountered in the use of radioactive sodium. After the measurements on a sample of radon are made, the ionization-chamber must be rinsed thoroughly by evacuation and flushing several times with a non-radioactive gas to remove all traces of the radon. Then the ionization-chamber must stand for three hours, or so, to permit the decay-products of radon, which were collected during the experiment on the central electrode, to decay into the long-lived radium D, having a negligible ionization. The Geiger counter when dipped into the solution of radioactive sodium, such as sodium chloride, can be washed quickly in water and immediately used again.

It would seem that for practical considerations and greater sensitivity, accompanied by ease in measurement and manipulation, artificial radioactive isotopes would still further enhance the tracer-technique outlined by Dr. Hess.

DETERMINATION OF THE EFFECTS OF WATERSHED-MANAGEMENT ON MOUNTAIN STREAMS

C. L. Wicht

Introduction

"It is possible, and indeed it is all too frequent, for an experiment to be so conducted that no valid estimate of error is available. In such a case the experiment cannot be said, strictly, to be

capable of proving anything. Perhaps it should not in this case be called an experiment at all, but be added merely to the body of experience on which for lack of anything better, we have to base our opinions."--R. A. FISHER on "The design of experiments", 1937.

Two forms of watershed-management cannot be compared by applying them in adjacent watersheds and contrasting the results. Watersheds vary so much in their hydrographic character that we can have no idea whether observed differences in flow are due to differences in topography, soil, geology, climate, or some other factor. This was, however, the method followed in the Emmental investigation in Switzerland, which was started by Dr. ARNOLD ENGLER in 1900 [see 1 and 2 of "References" at end of paper]. Notwithstanding the valuable and interesting experience gained in this study of the behavior of streams, the study can never be said to have proved anything as to the effects of forests on stream-flow.

An improvement was made in the experiment at Wagon Wheel Gap [3], started in Colorado in 1909. Here the stream-flow from two adjacent, apparently comparable, watersheds, with approximately similar forest-cover, was compared for nine to ten years before one watershed was denuded Observations were then continued to determine differences in the behavior of the streams after deforestation. Similar studies were carried out in southern California, where an accidental fire denuded one watershed in 1924, while an adjacent and more or less comparable watershed was left intact [4]. On the Wasatch Plateau in Utah, the effect of the cessation of grazing on one or two small over-grazed watersheds was similarly tested [5]. In these experiments one area was thus maintained as a control. In the analyses of data from them, it was possible to express stream-flow of one area in terms of stream-flow of the other. The regression of stream-flow of the second area on stream-flow of the first could, for example, be determined for the period before treatment, and this relation could be used for predicting flows of the second area after treatment. Differences between predicted and observed flows from the second area could then be considered to indicate the effect of treatment. Analyses carried out on these lines, first introduced into small-watershed research by HOYT and TROXELL [4], have yielded some indications of the effects of denudation on stream-flow.

Such experiments do not preclude the possibility that the results were invalidated by a change in climate or some other, possibly unsuspected, hydrographic factor, coincident with the application of the treatment. The success of the experiments depends on the assumption that the relation between the stream-flow of the two watersheds would have remained constant had no treatment been applied. Factors that influence stream-flow are not uniform in operation from place to place; in fact, they vary widely, often in different directions in relation to one another [6]. The author [7] has shown that the variability of stream-flow is also normally so great that a single comparison between two watersheds, or between two periods--before and after treatment--will be so burdened with chance-errors that the results must necessarily be uncertain.

In all these experiments no attempt was made to arrive at estimates of error [8]. The significance of observed differences was not tested, nor was the range in variation of such differences, within which they might be accepted with a predetermined degree of probability, estimated.

These experiments were inadequate in other ways. Thus, for example, Dr. W. C. LOWDERMILK [6] came to the conclusion that the locations of the experiments at Emmental and Wagon Wheel Gap and the contrasts in the treatments applied were not sufficiently representative of critical conditions.

Stream-flow investigations which have been inaugurated in recent years, but which have not yet developed far enough to yield results, have introduced many improvements [9,10]. They have benefited by experience gained in the above-mentioned pioneer studies. At the San Dimas Experimental Forest in California, for example, gaging-stations have been established on two large, two intermediate, and seven small watersheds [11]. The small watersheds are being treated to isolate the effect of vegetation. The watersheds are arranged in two groups and the main treatments are duplicated. In addition to the general expansion of the investigations and improvements in experimental design, the gaging of stream-flow, rainfall, erosion, and other technical operations have been improved [12,13,14].

At the Jonkershoek Forest Influences Research Station in South Africa, an experiment to establish the effects of watershed-management on stream-flow has been in operation since 1935. Two principal treatments are to be tested here: (1) Complete protection of the natural vegetation, which is sclerophilous shrub similar to the Macchie of the Mediterranean Region and the Chaparral of California; (2) uniform afforestation mainly with Pinus radiata D. Don. Other treatments involving broadcast burning and grazing are not to be so intensively examined.

It is the purpose of this paper to deal with some aspects of the technique, design, and interpretation of stream-flow experiments, with special reference to the investigation at Jonkershoek. Stream-flow experiments are large-scale, long-term projects involving high costs, and they should, therefore, be extremely carefully planned beforehand. Intensive work will probably not be resumed until after the war. No opportunity of discussing and planning post-war research should be allowed to pass, however, so that an immediate start may be made when the facilities to resume research are again available. In this case, the ultimate object should be to standardize technique, design, and methods of interpretation of such experiments.

Technique and design of stream-flow experiments

The precision of a stream-flow experiment can be increased by various means [15]. The accuracy with which the discharge of streams, the rainfall, and other factors is gaged can be improved. Careful supporting studies of climatic, topographic, geological, vegetational, and pedological features of the experimental area can be undertaken. The experiment can be enlarged by gaging the flow of a large number of streams, and repetition or replication of treatments can be introduced. None of these refinements should be neglected.

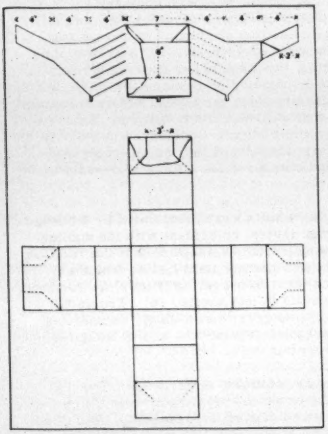

Fig. 1--Composite-gage with four vertical apertures (after Fourcade)

Gaging of precipitation and stream-flow--To determine the relationship of rainfall to runoff, it is essential to arrive at a reliable estimate of the volume of precipitation. In mountainous regions this is no simple matter, even when, as at Jonkershoek, no snow occurs. Recent research has shown that it is necessary to maintain a large number of gages because of the high variability of rainfall on such terrain [14,13], and that a special technique of gaging be employed [16,17].

In mountains it is particularly important to counteract the disturbing effect of wind on the catch of gages. For this purpose, the use of a suitable Nipher-type screen is generally recommended [16,17,18].

R. E. HORTON [19], quoted by BROOKS [16], pointed out that the catch of a horizontal orifice on sloping ground does not represent the true rainfall. R. GAIGER, S. PAGLIUCA, and C. F. BROOKS [16] showed that it was necessary to erect the gage and its windshield perpendicular to the surface of the ground. The catch must then be divided by the area of the orifice and by the cosine of its inclination in order to derive the true equivalent precipitation over the slope [17].

Dr. H. G. FOURCADE [17] has carefully considered the determination of rainfall over a watershed He has shown that the method of estimating the volume of water falling over the area, by assuming that it is equal to the product of the area with the rainfall measured in standard horizontal gages, can be very inaccurate. He describes a method by which the volume of rainfall can be measured by subdividing the area into a number of areas, on each of which the rainfall can be separately sampled by gages set perpendicular to the slope.

Standard, wind-protected gages should yield satisfactory estimates of the volumes of all types of rain, except mists. The gaging of mists may be important in localities where they are prevalent, and a record of such rain is specially valuable where interception by vegetation is being investigated. Dr. Fourcade has designed special composite gages to catch mists. One gage, to be used in conjunction with windshielded, horizontal, standard gages, has four vertical openings (Fig. 1). In order to catch the fine drifting particles, which often travel nearly horizontal, the wind-velocity is reduced inside the gage in a widening chamber, and at the end of this chamber a system of inclined baffles is provided, calculated to collect practically every particle of moisture. An estimate of the total volume of mist and other rain in the atmosphere, which might, for example, be intercepted by forest-canopy or other vegetation, may be made on the basis of readings taken with the Fourcade and wind-protected standard gages. The Fourcade gage will record more rain than is deposited on the ground. In strong wind when mist-particles are traveling nearly horizontal most

Fig. 2--Compound notched gaging weir used at Jonkershoek

of the time, practically no precipitation should be deposited on the ground. In such a case, the standard gages should record a negligible amount of rain, whereas the Fourcade gage may give relatively high readings.

The average direction and inclination of a rain may be estimated with the help of the Fourcade gage. This is done by determining the proportions of precipitation caught by the four vertical orifices, pointing north, west, south, and east, and by a horizontal gage.

In addition to the records of rainfall over watersheds, it is necessary in stream-flow studies to determine the volume of precipitation which penetrates through forest and other vegetation to the ground. One experiment on rainfall-interception by forest-canopy has been completed at Jonkershoek [20,21], and this work is being continued. Professor J. KITTREDGE, H. J. LOUGHEAD, and A. MAZURAK [22] have published an interesting account of an interception-experiment carried out on somewhat different lines, in a stand of Pinus canariensis Ch. Smith growing in California. In forested watersheds at Jonkershoek, the following method of determining the volume of rainfall-penetration will probably be adopted. A stratified random-sample (suggested in correspondence by Dr. H. G. WILM) will be taken over the watershed by selecting a large number of gaging-sites under the trees in groups and circulating a number of gages to the sites within each group. Both the groups and the gaging-sites within each group will be randomized. The number of gages used will depend on the variability of penetration under canopies of stands of Pinus radiata D. Don., which will be estimated by investigations now being conducted at Jonkershoek. The gages will have Nipher-type wind-screens attached, and will be set perpendicular to the slope. Readings from these gages will be corrected for stem-flow, on the basis of a stratified random-sample taken over the watershed. Stem-flow will be measured by leading the water into tanks in guttering attached around the boles of sample-trees.

Observations of the various stages in the dispersal of precipitation until it is ultimately delivered to streams as surface-runoff or seepage, or returned to the atmosphere through evaporation or transpiration, may be continued. Most important is probably the determination of the infiltration-capacity of the soil under various conditions. These data are yielded by runoff-plots and lysimeter-experiments. Particularly valuable should be observations made with a portable "infiltrometer" of the type described by P. B. ROWE [23]. This installation creates artificial rain and records runoff and infiltration. Observations can be carried out relatively rapidly on a large number of sites and under varying conditions. If evaporation- and transpiration-studies are included, the approximate evaluation of the complete hydrologic cycle should be possible. At Jonkershoek, all such intensive work has been postponed for the duration of the war. However, rain-gages and stream-flow recorders are being maintained.

The gaging of the smaller streams at Jonkershoek has presented no serious difficulty. Compound-notched weirs, all constructed on the same pattern (Fig. 2) with recorders, are used. They function very well, provided the stilling-pools are kept clean. Under the major treatments, erosion at Jonkershoek will probably not exceed "geologic norms" [24] and silting is always likely to be slight.

Selection of experimental watersheds and application of treatments--The discharge of eight watersheds will ultimately be recorded at Jonkershoek. Originally the author [25] considered that a number of treatments could be tested on these watersheds, but experience in analyzing stream-flow data in recent years has convinced him that more extensive repetition or replication of treatments should be introduced. Modifications to the approved program of research for Jonkershoek, therefore, have been recommended and these are awaiting official sanction. It has now been proposed that six watersheds should be combined into one major experiment to test the two treatments: (1) Total protection of natural vegetation; and (2) uniform afforestation mainly with Pinus radiata D. Don. Treatments involving burning and grazing in various intensities should be postponed for intensive investigation later, either on whole watersheds, or more probably by the runoff-plot method. For purposes of demonstration, and to obtain some advance experience, vegetation on one small-gaged watershed--Abdolskloof--will most likely be burnt every four years

Table 1--Treatments of six watersheds in proposed main experiment at Jonkershoek

Watershed	Gaging commenced	Age of plantation in year					
		1940	1948	1956	1964	1972	1975-80
Bosboukloof	1938	0	8	16	24	32	35-40
Biesievlei	1939	0	0	8	16	24	27-32
Tierkloof	1939	0	0	0	8	16	19-24
Lambrechtsbos-B	1943	0	0	0	0	8	11-16
Lambrechtsbos-A	Soon as possible	0	0	0	0	0	3-8
Langrivier	1940	0	0	0	0	0	0-0

without grazing. One 15-foot Parshall gaging-flume has been established on the Eerste River, the watershed of which includes three of the other experimental watersheds and is about 20 square miles in extent. The intention is to check the total effect of afforesting about 14 per cent of this watershed, because the river supplies water to the Municipality of Stellenbosch and irrigated farm-lands along its lower reaches.

The areas of the six watersheds in the proposed main experiment range from about 80 to more than 500 acres. The streams are tributaries of the Eerste River. All are, or will be, measured by means of notched weirs. With one exception--Abdolskloof--they include all watersheds within the forest-reserve on the northeast side of the river, that are well-defined, capable of being gaged and suitable for afforestation. They may be looked upon as a random-sample of an infinite theoretical population of watersheds on similar areas.

The same treatments--protection followed by afforestation--are proposed for all the watersheds except Langrivier, where afforestation is not contemplated (Table 1). We have thus a form of replication in time. Each watershed should be planted up to its fullest extent in one year. There should, however, be a period of eight years between the planting of successive watersheds. The dates of afforestation of the various watersheds have thus not been selected at random. The rotation of Pinus radiata D. Don. is 35 to 40 years here, and the fixed period of eight years has been chosen, so that ultimately a complete series of age-classes will be carried by the six watersheds taken together (Table 1), though each one will carry only one age-class. The effects of successive age-classes may thus be studied in each stream, while the total effect of a full series will be demonstrated by the flows of all six streams added together. A second main purpose of the repetition of afforestation at different dates on the various watersheds, instead of planting up all watersheds simultaneously after a period of protection, is to avoid a coincident change in climate which might mask the effect of treatment. In practice, the restriction in randomization of the dates of afforestation should have no serious effect on the estimation of errors.

Under protection, for the experimental periods planned, the natural vegetation is not likely to develop much further than the stagnant climax, or semi-climax Macchie stage, which it has now reached. Over a longer period of 100 years or more, scrub-forest composed of evergreen, indigenous trees may develop. The protected watersheds should, therefore, act as satisfactory controls.

The final interpretation of this experiment, if carried out as proposed, is not contemplated before the period 1975-80, and even then it may be considered worthwhile to continue the investigation. Long before this time, intermediate analyses will be undertaken, however, and as the experiment develops these analyses should yield progressively stronger, statistically sounder, evidence of the effects of the treatments.

Interpretation of stream-flow experiments

Stream-flow variables on which it is proposed to determine the effects of treatment are read from the hydrographs. The flow of streams may be divided into two parts--storm-flow and ground-water flow. It is generally required to obtain the maximum utilizable discharge from streams by reducing their variability, without too great a reduction of their total discharge. Normally, this entails converting the maximum possible volume of storm-flow to ground-water flow. In regions where floods and erosion are serious problems, the reduction of peak-flows is of special importance. In regions where shortage of water occurs in dry periods, the raising of low flows, or the reduction of the rate of depletion of ground-water flow, is the main concern. These considerations determine the choice of variables for investigation.

Table 2--Stream-flow statistics from annual hydrographs

Stream	Stream-flow year April to March	Total annual discharge, millions of imperial gallons[a]	Statistics from frequency-distribution of flow		
			Mean-flow, cfs	Standard deviation, σ	Coefficient of variation, v
Bosboukloof	1938-39	204	1.04	± 0.540	± 52.15
	1939-40	130	0.66	± 0.373	± 56.13
	1940-41	161	0.82	± 0.678	± 83.00
	1941-42	452	2.30	± 2.032	± 88.30
Biesievlei	1940-41	37	0.19	± 0.159	± 84.25
	1941-42	59	0.30	± 0.284	± 94.19
Tierkloof	1940-41[b]	327	1.66	± 2.943	±176.77
	1941-42[b]	630	3.21	± 4.295	±133.49
Eerste River	1940-41[c]	7,905	40.25	± 82.631	±205.29
	1941-42[d]	14,975	76.25	±131.634	±172.63
Abdolskloof	1941-42	16	0.08	± 0.048	± 56.33

[a]Imperial gallon = 0.16046 cubic foot. [b]Maximum capacity of gage exceeded for one hour. [c]Maximum capacity of gage exceeded for seven hours. [d]Maximum capacity of gage exceeded for 40 hours.

The procedure proposed for interpreting the effects of treatment is essentially the same for all stream-flow variables. The design of the main experiment at Jonkershoek and its interpretation have been so conceived that standard statistical principles apply, and the analysis of variance developed by R. A. FISHER [8] is suggested as most suitable. It is considered that this statistical approach opens the way towards finality in research on the effects of watershed-management on stream-flow.

In the following paragraphs proposed methods of determining the effect of treatment on the most important stream-flow variables will be outlined.

Total discharge--In order to evaluate the full seasonal fluctuations in discharge of streams, it is essential to use the year as the time unit when the effect of treatment on total discharge is being determined. In regions with a seasonal rainfall, the stream-flow year, commencing and ending just before the first rains, should be used [3]. At Jonkershoek, there is a pronounced winter rainfall-season, which has been described previously [26], and the stream-flow year has been fixed from April 1 to March 31. This insures that a relatively small volume of ground-water flow is carried over from one year to the next, and errors due to differences in discharge at the beginning and end of the year are reduced to an approximate minimum (see Fig. 4).

The total discharge of Jonkershoek streams varies considerably from year to year, and from watershed to watershed (Table 2). Unless the effect of treatment is pronounced, observations over a very long series of years, therefore, will be required to prove the significance of differences due to treatment. It is indeed doubtful whether slight effects could ever be experimentally demonstrated by merely lengthening the experimental period, because climatic cycles and other disturbing long-term changes come into play.

In the relatively small, steep watersheds of Jonkershoek there is, however, a strong regression of total annual discharge on total annual precipitation (Fig. 3). In an analysis of variance [8] of total annual discharge, it is thus possible to reduce the estimated variance due to error by subtracting variance due to differences in wetness of years, as well as variance due to differences in size and other features of watersheds.

Because of the number of repetitions of treatments, the proposed experiment at Jonkershoek should yield statistically significant results, even if the effect of treatment on total discharge is slight.

Differences in total monthly or seasonal discharges may be tested on similar lines, in order to determine whether treatment has had any effect on the general distribution of discharge over the year.

Variability of flow--The Jonkershoek streams are extremely variable or "flashy" in rate of flow (Fig. 4). They respond immediately to rain, and stages fluctuate rapidly. Slower, steadier variations in rate of flow are due to accretion and depletion of ground-water flow. In order to

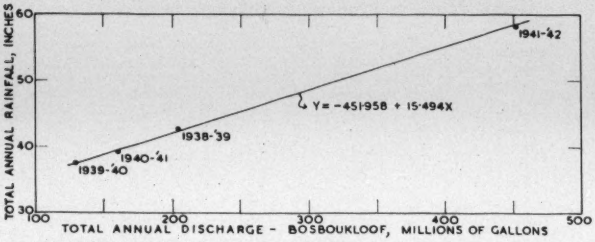

Fig. 3--Regression of total annual discharge on total annual rainfall

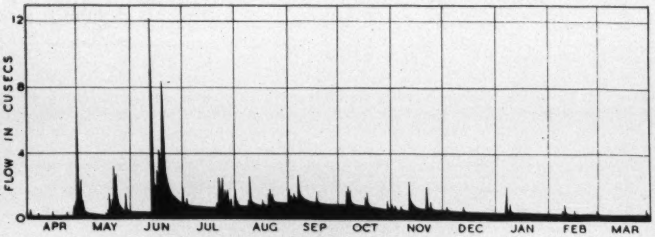

Fig. 4--Hydrograph, Bosboukloof, 1940-41

evaluate and examine these main variations in flow numerically, hourly readings are taken from recorder-charts. Minor variations, in the form of diurnal fluctuations due to evapo-transpiration losses, are investigated separately.

Frequency-distributions (Fig. 5), obtained if the hourly readings are sorted into rate-of-flow classes, have been shown to be asymmetrical and strongly leptokurtic at Jonkershoek [7]. From these distributions the standard deviation, σ, a suitable measure of the dispersal of observations about the mean or the general variability of the rate of flow, can be computed [8]. Instead of σ, Pearson's coefficient of variation, ν, an absolute measure of dispersion, which is independent of the mean rate of flow, may also be used. These statistics reflect the general degree of steadiness of the stream; they do not indicate when either peak-flows or low flows have been influenced in a particular direction. Although the distributions from which they have been computed are not "normal", they may safely be used to compare variability in rate of stream-flow, as long as the shape of the distributions does not change [27].

Values of σ and ν for streams of Jonkershoek are given in Table 2. These variables, like total discharge, differ greatly from year to year and from one stream to another. Investigations aimed at accounting for some of this variation are still being undertaken. In addition to variance due to differences in watersheds, it would appear likely that, in a final analysis, a regression of annual variability in rate of stream-flow on annual variability in precipitation, should account for a large portion of the total variance.

Ground-water-flow--The main hydrological engineering problem in the Jonkershoek Region is to maintain sufficient water-supplies during the critical, dry, summer months of January to March. Special attention is, therefore, being devoted to studies of ground-water flow.

Low flows in streams depend on the degree of saturation of ground within the watershed, the length of time elapsing since the last rain, and the rate of depletion of ground-water flow. The degree of saturation of ground in the watershed during dry weather determines the rate of flow in the stream at that time. If we wish to determine the effects of a treatment on low flows, we need, therefore, only to examine the depletion-curve of ground-water flow, from which may be read

the depletion from any desired stage of flow and for periods of drought of various lengths.

In a previous publication [28] a method of computing complete average depletion-curves, from all the observations of ground-water flow made within any given period, was described. This method of computation makes it possible to apply the theory of probability and so test the statistical significance of differences between the depletion-curves.

To derive depletion-curves in this way, it is necessary first to determine the regression of

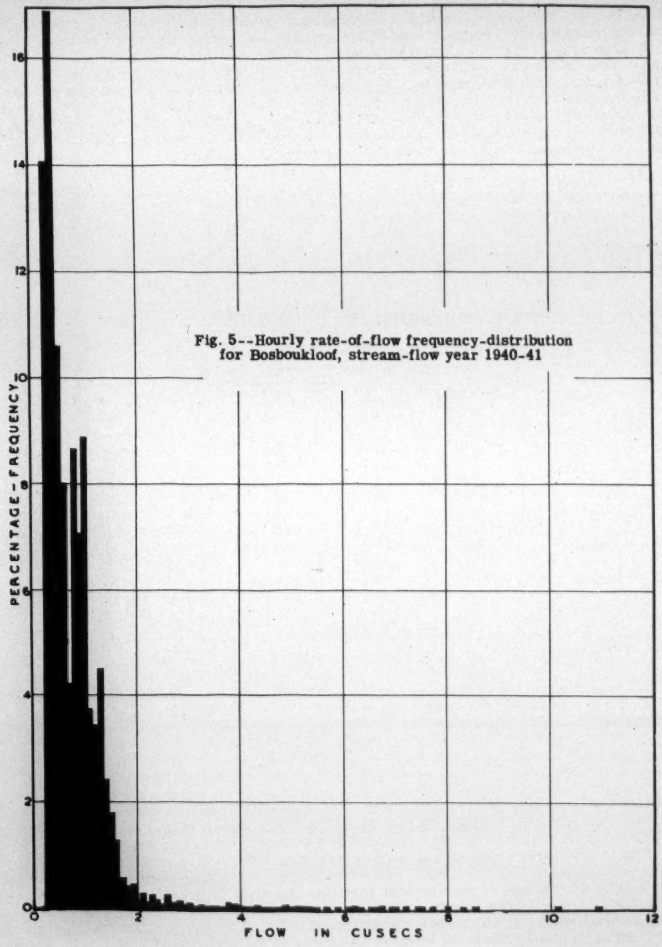

Fig. 5--Hourly rate-of-flow frequency-distribution for Bosboukloof, stream-flow year 1940-41

ground-water flow after a unit-period of depletion on initial flow before depletion. This regression, which is linear, is a simple useful statistic, suitable for demonstrating the nature of ground-water flow. The regression-function at Jonkershoek is

$$Q_{(n+1)} = (a + bQ_n) \qquad (1)$$

where Q_n is initial discharge, $Q_{(n+1)}$ is the discharge after a unit-period of depletion, and a and b are constants.

An entirely satisfactory explanation of the constant a has not been found so far. It indicates that streams do not deplete to zero, but down to a constant base-flow. Its values are relatively low for all Jonkershoek streams. This characteristic of flow is being investigated further. The constant b--the coefficient of depletion of ground-water flow--reflects the average rate of depletion of the stream, provided the unit-period of depletion is kept constant. A treatment causing increased rate of depletion through greater evapo-transpiration losses from the watershed or deterioration of ground-water storage, should lead to a lowering of the values of the coefficient. A treatment causing stabilization of ground-water flow should raise the values of the coefficient. Differences between coefficients can be statistically tested.

If the unit-period of depletion is taken as two days, the coefficients for Jonkershoek streams with watersheds under natural vegetation, are all about 0.9 (Table 3). This indicates that the conditions for ground-water storage and seepage into streams, are more or less uniform throughout the area. (Although Bosboukloof was planted in 1940, the trees were still too small to have any effect on stream-flow in the year 1941.)

Table 3--Values for constants in annual, linear regressions for two-day depletion-period [equation (1)] and depletion-curve functions [equation (2)]

(No readings taken earlier than five days after spates)

Stream	Calendar year	No. of observations	Values in equation (1) a	(1) b	(2) $\frac{a}{(1-b)}$	(2) $\sqrt{b}$
Bosboukloof	1938	116	1.375	.937	21.8	.9680
	1939	164	3.616	.860	25.8	.9274
	1940	127	2.013	.901	20.3	.9492
	1941	96	7.139	.888	63.7	.9423
Biesievlei	1940	111	0.690	.860	4.9	.9274
	1941	102	0.303	.902	3.1	.9498
Tierkloof	1940	107	2.036	.901	20.6	.9492
	1941	89	3.369	.908	36.6	.9529
Eerste River	1940	74	8.936	.874	70.9	.9349
	1941	60	15.998	.897	155.3	.9471
Abdolskloof	1941	140	0.054	.959	1.3	.9793

Note: In future analyses these values will be computed for stream-flow years.

The following function for depletion-curves of ground-water flow given in equation (2) has been derived from the function for depletion-regressions [28], with the assistance of Professor J. T. MORRISON.

$$Q_t = [a/(1 - b)] + [Q_o - a/(1 - b)] \sqrt{b}^t \qquad (2)$$

where Q_o is initial discharge, Q_t is discharge after depletion-period t, and a and b are the same constants that appeared in the regression-function for depletion. If the constant a is zero this function resembles that which R. E. HORTON [29] derived for such curves from theoretical considerations in 1904. In Horton's function $\sqrt{b}$ is replaced by e^{-c} where e is the Naperian base and c is a constant. Figure 6 shows a depletion-regression and the depletion-curve derived from it.

Variations in a from year to year in these functions appear to be correlated with the wetness of the years. The data available at present are, however, insufficient to establish this point. Further investigations will probably show that the rainfall-factor should be taken into consideration when it is proposed to demonstrate the effect of treatment on the depletion of ground-water flow.

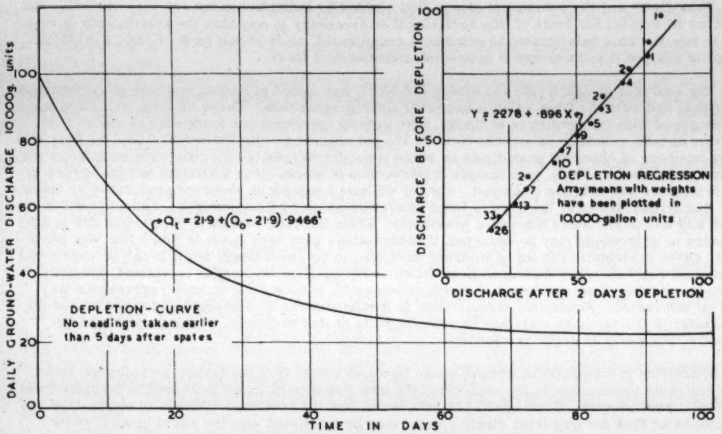
DAILY GROUND-WATER DISCHARGE 10000s units
TIME IN DAYS
$Q_t = 21{\cdot}9 + (Q_0 - 21{\cdot}9) \cdot 9466^t$
DEPLETION-CURVE
No readings taken earlier than 5 days after spates
DISCHARGE BEFORE DEPLETION
DISCHARGE AFTER 2 DAYS DEPLETION
Y = 22·78 + ·896 X
DEPLETION REGRESSION
Array means with weights have been plotted in 10,000-gallon units

Fig. 6--Linear regression and curve of ground-water flow-depletion, Bosboukloof, 1940-41

The ground-water discharge of streams may be separated from that derived from stream-flow by the use of ground-water depletion-curves [29,30]. It thus becomes possible to estimate the total annual flow-discharge of ground-water. This variable will be dependent on the wetness of the years, and the effect of treatment on it may be tested by the same procedure used for total annual discharge. The relative volume of annual flow-discharge of ground-water is derived by expressing that discharge as a percentage of total annual discharge. Significant increases or decreases in this percentage after treatment will show whether a greater volume of precipitation is being converted into ground-water flow or not.

Ground-water flow has thus far been considered without regard to diurnal fluctuations, which are caused by daily evapo-transpiration losses along the stream-courses [31,32,33,34]. It may be assumed that the daily losses occur in the stream-channel or in its immediate vicinity, and that only ground-water which has reached the stream-bed is affected by these fluctuations.

Indirect, relative estimates of the consumptive use of water along streams may be based on these fluctuations. If the periods of relatively level flow which separate the daily depressions in Jonkershoek streams are connected by a straight line, the area enclosed by the fluctuation-curve and the interpolated line will give such an estimate of the volume of water lost to the stream on that particular day.

Daily water-losses computed in this way are correlated with factors of weather controlling evaporation and transpiration. In comparisons to determine the effect of treatment on consumptive use of water along streams, the regression of daily losses on evaporation-capacity--evaporativity--of the atmosphere may thus be used. If readings with, say, Livingston-Thone atmometers are not available, the regression on maximum daily temperature, though not so satisfactory, may be substituted [34]. Such regressions computed at Jonkershoek are nearly linear. Characteristic regression-coefficients are obtained for different watersheds and seasons.

Storm-flow--Studies of storm-flow at Jonkershoek are not yet far advanced. The methods of analysis probably to be adopted when dealing with storm-flow variables will, however, be indicated.

The total annual discharge of storm-flow is obtained by subtracting the total annual flow-discharge of ground-water from the total annual discharge. It should be closely correlated with the wetness of the years. The relative total annual storm-flow discharge is obtained in the same way as for ground-water flow. The interpretation of the effects of treatment on these variables is carried out as for other variables dealt with before.

Peak-flows and the volumes of storm-flow yielded by individual rains are very variable, and in order to account for some of this variation it is necessary to consider the relationship of rainfall to runoff. This relationship is extremely complicated, as is shown by R. T. ZOCH'S [35] attempt to analyze it and express it in precise mathematical form.

The analyses of ZOCH [35] and others [29,36,37] are aimed at finding methods of synthenizing individual hydrographs from rainfall and other hydrographic data. These studies, which are mainly concerned with the prediction of floods, have greatly increased our knowledge of storm-flow. In experimental research on stream-flow we are not concerned with individual flows; we deal with large numbers of observed peak-flows or storm-flow discharges, which constitute samples of statistical populations. From such sample-observations of storm-flow, statistics and the errors to which they are subject, are computed. Thus if we have a sample of observed peak-flows or storm-flow discharges, the total variance of these observations may be computed [8], and analyzed in the same way as for variables discussed previously. From the total variance, the portion due to differences in watersheds may be deducted, if observations have been made in more than one watershed. Other systematic causes of variance have still to be established, but if it can be shown that significant regressions of individual peak-flows or storm-flow discharges on volume, intensity, duration, or other characteristics of precipitation exist, variance due to such regressions may also be subtracted. Finally the variance due to treatments can be computed and deducted and the remainder of the variance may then be considered to be due to chance. On this portion of the variance, estimates of error are based.

In addition to investigating ground-water flow and storm-flow separately as indicated above, it is desirable to examine, in the same way, the total volumes of water delivered to streams from individual rain-storms. T. IWASAKI [38] has shown how the combined volumes of storm-flow and ground-water flow derived from single storms may be estimated with the aid of ground-water depletion-curves.

Conclusion--The analyses of variance for all stream-flow variables selected for investigation permit the application of statistical tests of significance [8]. If differences due to treatment have caused only a relatively small portion of the total variance the effects of treatment will be shown to be insignificant by the Z-test. If treatments have had significant effects, the significance of differences in flow caused by individual treatments may be examined by applying the t-test. For the Jonkershoek investigation, these tests will show whether it has been experimentally proved that afforestation of ground under protected natural flora has increased or decreased the values of selected stream-flow variables; and, if significant differences have been caused, they will show further, with what degree of precision these have been evaluated by the experiment.

Summary

In this paper some aspects of the technique, design, and interpretation of stream-flow experiments are considered, with reference to an investigation at Jonkershoek, Stellenbosch, South Africa.

The gaging of precipitation in mountainous regions, and penetration of rainfall through forest-canopy are discussed.

A proposed experiment is described in which it is suggested that two treatments--total protection of natural vegetation, followed by afforestation mainly with Pinus radiata D. Don.--should be tested by repetition on six watersheds.

Methods of interpreting stream-flow data to demonstrate the effects of various types of watershed-management are suggested. Stream-flow variables relating to total discharge, variability of flow, ground-water flow, and storm-flow are selected for investigation. The application of the analysis of variance developed by R. A. FISHER [8,15] to test the significance of differences in flow caused by treatments and to show with what degree of precision these differences have been evaluated, is recommended.

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DISCUSSION

C. R. HURSH (U. S. Forest Service, Appalachian Forest Experiment Station, Asheville, North Carolina)--The author is to be commended on raising a point that is of vital significance in the field of research on watershed-management employing complete drainage-areas. The point is whether or not it is feasible to substitute statistical design and methodology in place of a knowledge of physical processes on experimental drainages. The author points out that variability is to be expected in the climatic factors of the locality of Jonkershoek, and that this may have a possible effect on the comparative response of the different drainage-areas. He would like to eliminate through an experimental design the effects of these yearly climatic differences. Also, he would like to eliminate through statistical methods the factors of size, shape, soil-depth, and other physical factors of watersheds, in order to test the effect of a controlled change in the vegetative cover. The analysis of variance and other statistical methods proposed by the author are recognized tools of research. No one could question the desirability of sound statistical methods in the analysis of watershed-data, and of exploring where they apply to watershed-studies. The question is only one of how they may be used most advantageously with our present inadequate knowledge of physical processes that control water-cycle factors.

A topographic map of the Jonkershoek watersheds is imperative to understanding the author's experimental problem. Such a map has already appeared in two previous foreign publications by the author [see 1 and 2 of "References" at end of this discussion], and is reproduced here for the convenience of American readers as Figure 1. These two publications also furnish pertinent background-information to Mr. Wicht's present paper. Annual rainfall for the region ranged for the years 1938-42 from 38 to 58 inches. By far the larger proportion of rainfall occurs during the winter, and the principal vegetation is a chaparral-cover which is described as being not unlike that found in southern California.

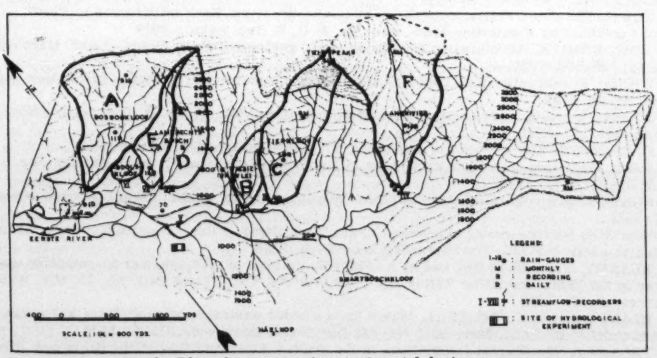

Fig. 1--Plan of Jonkershoek experimental drainage-areas

Geological conditions are doubtless an exceedingly important factor in ground-water storage and ground-water flow in the Jonkershoek streams. LaROCQUE [3] has shown how geology may be related to runoff in the Santa Ynez River-Basin in California, an area that appears to have much similarity to Jonkershoek. Referring to the map of Jonkershoek in Figure 1, it will be seen that the watersheds include many precipices that reach altitudes of 5,000 feet. A portion of each watershed, with the exception of B, is very steep and probably differs in geology and soil-profile from the rest of the same watershed. This extreme difference in soil-conditions over a single experimental watershed may produce runoff that is a composite of two very different types of soil-profiles, each having its own hydrologic characteristics. Whether this is true could be determined on Area C, for example, by installing a second stream-gage at elevation 2,200 feet. Secondary gages on other areas could also be installed. In the author's proposed design for the major experiment, Area B is given the same consideration as all the other areas, whereas its geology is apparently significantly different from the rest. Area F is to be used as a permanent experimental control for the other watersheds.

A comprehensive interpretation of stream-flow experiments will doubtless require more than the establishment of a statistical significance of a change in total annual discharge and variability of flow, which the author suggests in his summary as being suitable for investigation. It will be necessary to go much further into a complete analysis of the water-cycle, including water-storage phenomena within the soil-profile, if watershed-management techniques are to be interpreted into practical terms. The author has indicated this fact under the heading of "Technique and design of stream-flow experiments". Referring to FISHER [4] in regard to increasing the precision of stream-flow experiments, the author states that careful supporting studies of climatic, topographic, geological, vegetational, and pedological features on the experimental area can be undertaken, and that none of these refinements should be neglected. However, the author does not introduce this thought into his major experimental design. These may be the real factors that should enter into a statistical analysis rather than be eliminated by statistical design. Perhaps these supporting studies should precede the adoption of a final design for the major experiment at Jonkershoek. These so-called supplementary studies may indicate that the hydrologic characteristics of the experimental watersheds are so strongly controlled by geological and pedological features, for example, that a man-made change in type of vegetation from chaparral to pine on a portion of a watershed will be an insignificant factor in runoff.

ROWE [5] concludes from his studies in the Sierra Nevada foothills "that the natural cover of woodland chaparral-vegetation, by decreasing surface-runoff and erosion, and by serving to regulate and prolong stream-flow from the area, at little or no reduction in the quantity of water-yield, is highly beneficial in the production of usable water"

The major objective of the research, as stated by the author, is to develop practical watershed-management that will favor ground-water flow. One must raise the question: Why the author has not stressed the possibility of insuring maximum flow in summer by the removal of riparian vegetation both along the valley-bottoms and also adjacent to the mountain stream, continuing up their very sources? The general conclusions of studies in this country, for example, those of TROXELL [6], point to the removal of riparian vegetation as being of first-line importance in maintaining maximum ground-water flow during the growing season. Removal of the vegetation in this case must not be confused with the destruction of the natural soil-profile that might follow heavy logging and burning. It implies only the cutting of the vegetation to reduce transpiration with a minimum of disturbance of the type of humus. It might imply the repeated cutting of the major vegetation at intervals whenever it has again become reestablished. Here arises the question of what type of vegetation will maintain favorable infiltration and ground-water storage with the least water-requirement. If this is the problem at Jonkershoek, could not the relative water-requirements of pine as compared to chaparral be tested by more suitably controlled methods than the use of unlike watersheds each with an indefinite number of uncontrolled variables?

In studying the effect of watershed-management on mountain streams, the number of variables which are not susceptible to control are likely to be far greater than the controlled. Also, the actual effects of different variables of watershed on stream-flow are not well known. Their interactions are exceedingly complex. Important among these variables operating on a single watershed are geological structure, soil-profile, and amounts and distribution of rainfall. These vary within the individual watersheds as well as among different watersheds. This in itself may not prevent the use of analysis of variance. However, because so little is known as to how to best define variables of watershed and their effect upon stream-flow, this may create a real difficulty in making final interpretations of results. For instance, it will be necessary to establish a relative hydrologic value of different soil-profiles on different portions of one watershed. What is to be the relative values to be assigned to soil-properties on different watersheds? Obviously, from

the nature of the topography, geology, and stream-patterns of the Jonkershoek drainage-areas, the subject of the hydrologic characteristics of different soil-types is going to be an exceedingly difficult, but at the same time a very essential factor. Hydrologic characteristics of the different soil-profiles present will eventually have to be evaluated in some manner as a phase of practical watershed-management.

The author states in a previous publication that it will not be possible to afforest the same percentage of area on each watershed and consequently the effect of rate of growth and density of stand on each watershed will also vary, all of which will introduce some complications. If one could accept as a hypothesis that the six watersheds in the author's major experiment can be compared based on their geologic and pedographic characteristics, then the design of the major experiment proposed has its attractive features. It has the value of reducing the climatic effect of individual years to a minimum. It allows for duplication of treatment with time. It does not permit comparison of maximum effect expected from the older age-classes of the plantations, being best suited to determine the effects of immature and young stands. However, this could be taken care of by allowing the study to continue for another 24 years or more after 1980. At the end of the present period, 1975-80, only one-fifth of the observations will be from the three watersheds with plantations over 16 years of age.

Statistical methods will become of increasing importance in hydrologic research. However, it is possibly too soon to state that any one method such as the analysis of variance "opens the way toward finality" in research on watershed-management. One would hope that even more promising methods taking into account more of the difficulties peculiar to analysis of watersheds can be developed. At the present stage of watershed-research, statistical methods offer tremendous help in improving the sampling of the different component factors of the hydrologic cycle such as precipitation over watersheds, interception by vegetation-canopies, soil-moisture, etc.

The discussor has found that observation-wells have been a valuable aid to understanding underground storage and movement of water on mountain drainage-areas. These may also have an important place at Jonkershoek.

It is possible that the author has dismissed without sufficient trial the concept of standardization of hydrologic characteristics of a single watershed over a period of years. Then after its constancy of behavior has been established, the area is observed for a second period following an experimentally controlled change in vegetative cover. This procedure at least has an advantage in that the physical characteristics of one watershed do not have to be compared with those of another. In Figure 3, the author has shown that for an individual watershed, the annual (RO/P)-ratio is fairly constant regardless of the amount. May this not mean that it is the annual base-losses to runoff that remain constant, and that additional P over this base is directly proportional to the increase in RO? The vegetation may have adjusted itself to the minimum yearly precipitation. If these hypotheses are true, then the extreme precaution of developing a design to eliminate the climate effects of a single year may not really be such an important factor.

Theoretically, the author's design for his major experiment would eliminate the climatic effect of the individual year, but at the same time it has thrown into a common average all physical differences within and between individual drainage-areas. Practical watershed-management will advance through an increasing knowledge of the physical processes involved in the hydrology of land-areas. Purely statistical analyses of runoff-records may not in themselves advance the knowledge of these physical processes.

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THE FLOOD-HYDROGRAPH AND VALLEY-STORAGE

Howard M. Turner

In a paper presented last year by Professor BARROWS [see 1 of "References" at end of paper] the flood inflow-hydrograph was developed from the flood-hydrograph by the use of a storage-relation determined from the recession-curve.

The chief criticism made in the discussion of this paper was of the basic assumption that the storage figured from the recession-curve is applicable to the rising stage. The writer does not take exception to this, as will be described later. He has found, however, that the flood-hydrograph does not lend itself in this way to a determinate result for the inflow.

In a paper presented before the Hydraulic Section of the Boston Society of Civil Engineers by the writer and ALLEN J. BURDOIN [2], the storage-curve for given flood-hydrographs was computed from the recession-curve by the general storage-formula using the base-flow as the inflow, I, and the flood-flow as the outflow, O.

$$(t/2)\ (I_1 + I_2) + S_1 = (t/2)\ (O_1 + O_2) + S_2$$

A rational inflow-hydrograph, trapezoidal or triangular, was developed with a total flood-runoff volume equal to that of the actual hydrograph above the base-flow and taking into account--the length of rainfall assumed uniform, the concentration-time and the requirements of the flood-hydrograph itself as to time of cessation of inflow and intersection of the inflow- and outflow-hydrographs at the peak of the latter. The storage obtained from the recession-curve was then applied to this inflow-graph on both rising and falling stages to produce the outflow--that is, the flood-hydrograph. In the aforementioned paper the following was stated:

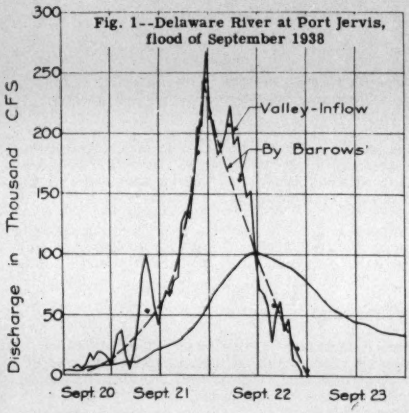
> "It may be questioned why it is not better, using the general storage-equation and the storage-curve, to figure back from the actual outflow-hydrograph to the inflow-hydrograph instead of assuming, as is done here, an inflow-hydrograph and then computing the outflow-hydrograph. It may be that this can be done but difficulty has been found in cases tried because small differences in slope of the actual hydrograph may throw off the result. This should be the subject of further study."

This use of the storage from the recession-curve to figure the inflow-hydrograph back from the actual flood-hydrograph was the method adopted in Professor Barrows' paper and the writer still finds the same difficulty in applying it. Referring to the example given of the flood of 1938 on the Delaware River at Port Jervis, the writer takes the same exception, as was taken in the discussion, to the valley-storage curve on Figure 1 being plotted as a straight line, because if the next higher point were plotted it would show that the straight line is not the best fit that can be made for this curve. However, in the following discussion the writer has used Professor Barrows' storage-curve as shown. The difficulty in getting satisfactory results may be shown as follows:

In the computation the intervals chosen for both outflow and inflow were 10,000 second-feet, starting with 10,000 second feet. The peak-flow was found to be 242,000 second-feet. Other intervals give different results; if intervals of 7,000 second-feet are taken (starting at 12,000) the highest point becomes 267,000 second-feet. In effect, the selection of any such intervals is a smoothing of the hydrograph, but the smoothing of the hydrograph with such steep slopes is hazardous. With intervals of 7,000 second-feet, it is found that the highest peak is established by 55-minute flow, which is about 54,000 second-feet in excess of a high general level. During this 55-minute period, 210,000 second-feet go into storage and an error of ten minutes in time will correspond to about 35,000 second-feet in the peak. In order to check this further the same method was used, but taking all the data--that is, the hourly discharge as given in the flood-record. This gave the results shown in Figure 1. The inflow-hydrograph thus obtained has a larger runoff-volume than the actual hydrograph. The reason for this has not been investigated. Clearly this ought to have some smoothing, but the difficulty is to know how. There are many smoothed inflow-hydrographs with peaks from about 217,000 to 267,000 second-feet that would serve without departing far from the actual hydrograph.

The chief question raised in the discussion of this paper was as to whether the use of storage determined from the recession-curve can be applied to the rising stage, the basic assumption used by Professor Barrows and the writer in his study referred to above.

The location of the storage evidenced by the recession-curve may have some bearing on this



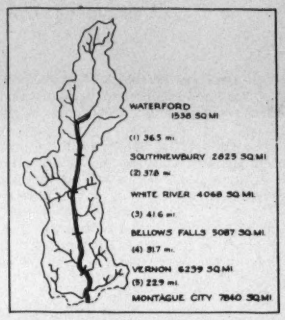
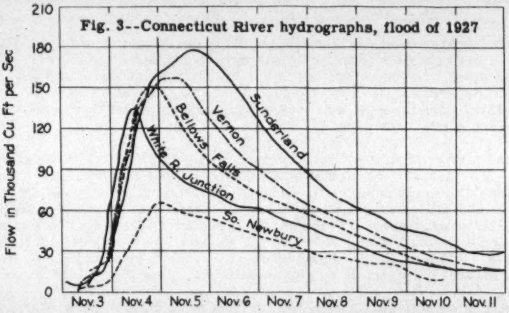


Fig. 2--Connecticut River, drainage-area above Montague, Massachusetts



question. The curve of storage against output from the recession-curve of the flood of 1927 on the Connecticut River at Sunderland, Massachusetts, was computed and showed a straight line from the base-flow of 10,000 second-feet to the point of recession at 150,000 second-feet [2]. In the flood-study of the Connecticut River [3] the United States Army Engineers measured the valley-storage in the main river-valley at peak-flow for this flood, and the flood of 1936, including some short distances up tributary streams, for five reaches above Montague, Massachusetts, as shown in Figure 2. (The gaging-station at Sunderland, Massachusetts, in 1927, was later moved upstream to Montague; the slight difference between the two points has been neglected in this paper.) For their flood-routing computations they also computed curves for storage in each reach which checked very well with the measured storage. With these curves and the hydrographs in Figure 3 giving the flow at the downstream end of each reach, the total amount of storage in this portion of the main river-channel at any time can be determined after the time the recession started at Sunderland, about 2 o'clock on November 6, when the flow was 150,000 second-feet.

Tables 1 and 2 and the curves in Figure 4 show, from the data of the United States Army Engineers, the storage for different flows. Curve 1 is based on the Army Engineers' computed storage-curves. The residual storage which these curves show at zero-flow was deducted in order to give zero-storage at zero-flow. Curve 2 shows the sum of the measured storage of the five reaches at the peak of the flood of 1927 with a straight-line reduction to zero at zero-flow. Curve

Table 1--Storage in Connecticut River Valley, Montague, Massachusetts, to Waterford, Vermont, flood of November 1927, from United States Engineer's computed values

[The residual storages at zero-flow have been deducted; if added the total storage would be increased by 3.74 billion cubic feet (bcf)]

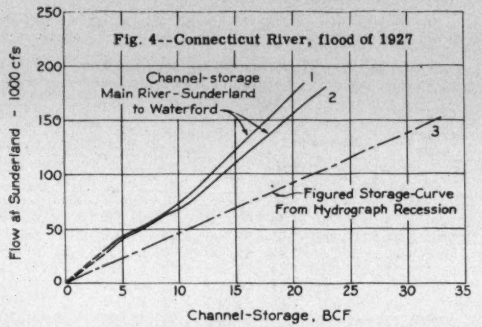
Date	Time	Sunderland, Massachusetts		Vernon, New Hampshire		Bellows Falls, Vermont		White River, Vermont		South Newbury, New Hampshire		Total storage
		Q	Storage	Q	Storage	Q	Storage	Q	Storage	Q	Storage	
	h	cfs	bcf	cfs	bcf	cfs	bcf	cfs	bcf	cfs	bcf	bcf
Nov. 6	14	150,000	4.63	103,000	3.35	82,000	3.63	63,000	2.98	46,000	2.75	17.34
	24	126,000	3.87	87,000	2.85	74,000	3.23	64,000	2.98	42,000	2.50	15.43
Nov. 7	12	109,000	3.40	75,000	2.47	65,000	2.85	55,500	2.59	36,000	2.15	13.46
	24	89,000	2.77	65,000	2.14	57,000	2.50	51,000	2.37	31,000	1.87	11.65
Nov. 8	12	73,000	2.30	56,000	1.85	50,000	2.19	41,500	1.98	28,000	1.68	10.00
	24	63,000	2.00	50,000	1.65	42,000	1.82	33,000	1.55	22,000	1.30	8.32
Nov. 9	12	55,000	1.75	42,000	1.38	35,000	1.53	26,000	1.20	20,500	1.22	7.08
	24	47,000	1.50	34,000	1.12	26,000	1.14	22,500	1.05	14,000	0.83	5.64
Nov. 10	12	43,000	1.38	27,000	0.90	21,000	0.92	19,000	0.87	10,000	0.58	4.65
	24	34,000	1.08	22,000	0.73	17,000	0.75	16,500	0.77	8,000	0.45	3.78
Nov. 11	12	29,000	0.94	19,000	0.62	17,000	0.75	16,500	0.77	8,000	0.45	3.53
	24	29,000	0.94	16,000	0.53	16,000	0.70	16,500	0.77	8,000	0.45	3.39

Table 2--Storage in Connecticut River Valley, Montague, Massachusetts, to Waterford, Vermont, flood of November 1927, measured values--at 1927 peak--straight-line reduction to 0 at 0 cfs

Date	Time	Sunderland, Massachusetts		Vernon, New Hampshire		Bellows, Falls, Vermont		White River, Vermont		South Newbury, New Hampshire		Total storage
		Q	Storage	Q	Storage	Q	Storage	Q	Storage	Q	Storage	
	h	cfs	bcf	cfs	bcf	cfs	bcf	cfs	bcf	cfs	bcf	bcf
Nov. 6	14	150,000	4.47	103,000	3.77	82,000	3.45	63,000	3.10	46,000	4.12	18.91
	24	126,000	3.72	87,000	3.17	74,000	3.08	64,000	3.17	42,000	3.73	16.87
Nov. 7	12	109,000	3.22	75,000	2.72	65,000	2.72	55,500	2.70	36,000	3.22	14.58
	24	89,000	2.63	65,000	2.37	57,000	2.37	51,000	2.50	31,000	2.78	12.65
Nov. 8	12	73,000	2.17	56,000	2.03	50,000	2.07	41,500	2.02	28,000	2.50	10.79
	24	63,000	1.85	50,000	1.82	42,000	1.75	33,000	1.57	22,000	1.97	8.96
Nov. 9	12	55,000	1.62	42,000	1.53	35,000	1.43	26,000	1.27	20,500	1.80	7.65
	24	47,000	1.40	34,000	1.25	26,000	1.07	22,500	1.12	14,000	1.25	6.09
Nov. 10	12	43,000	1.28	27,000	1.00	21,000	0.85	19,000	0.95	10,000	0.92	5.00
	24	34,000	1.00	22,000	0.80	17,000	0.68	16,500	0.81	8,000	0.72	4.01
Nov. 11	12	29,000	0.87	19,000	0.70	17,000	0.68	16,500	0.81	8,000	0.72	3.78
	24	29,000	0.87	16,000	0.59	16,000	0.65	16,500	0.81	8,000	0.72	3.64

3 shows the computed storage from the recession-curve of the Sunderland hydrograph. The storage in these five reaches, which represent only 60 per cent of the total length of the main river above, contains about 60 per cent of the total storage in the whole river-system shown by the recession-curve. It is also found, as shown on the Table, that about 45 per cent of this main river-storage was in the two lower reaches. When the time of travel of "up-river storage" to the station is taken into account,, it is evident that the main river-storage close to the station must be a very effective part of the total storage. This value of the lower storage is further confirmed by a similar computation for the flood of 1938, in which the total storage in the same five reaches of the river was found to be 15 per cent less than in 1927 and the storage in the two lower reaches only about five per cent less.

The three large recent floods on the Connecticut River were quite different. The flood of 1927, shown in the hydrographs on Figure 3, was mainly an up-river flood; the flood of 1936 was a general flood imposed on a large base-flow; the flood during the hurricane of 1938 was a down-river flood. The writer found, however, substantial agreement in the recession-curves in spite of



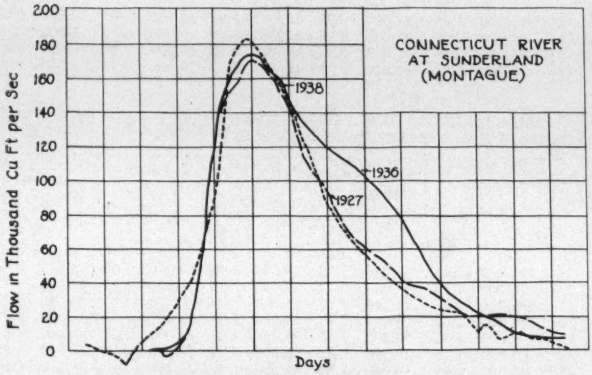


Fig. 5--Flood-hydrographs above the base-flow

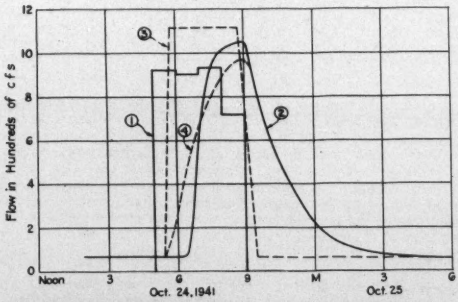


Fig. 6--Flow of Deerfield River at West Deerfield, Massachusetts (588 sm) and discharge from No. 2 Station, New England Power Company

this difference [2]. Also, in spite of the difference in location and time-distribution of rainfall the hydrographs on the rising stage as shown by Figure 5 are surprisingly close. The hydrographs of these three floods should have shown greater differences unless there had been some influence to bring them together. The storage in the main river-channel near the station would have this effect. The uniformity of the distribution-graphs for a given station for different floods also appears as evidence of this effect. It would appear that the storage immediately above the station must have a great deal to do with determining the hydrograph-shape.

The Connecticut River, used in these examples, is a stream particularly favorable to flood-analysis owing to the symmetrical shape and tributary pattern of the drainage-area. The writer has studied floods on other streams of comparable size and believes that they will show the same general results though he has not studied very small drainage-areas or very large ones. The uniformity of the unit-graph and the distribution-graphs, however, is not a property of the Connecticut River alone.

If the storage in the main river-valley and chiefly that immediately above the station is a controlling factor, the storage in the rising stage should not be very different from that in the falling stage. This becomes a routing-problem and the only difference would be that caused by the changing slope of a rising and falling river. The writer has not figured this but believes that this correction would be small in most cases. As Professor Barrows pointed out in his closing discussion, except in extreme cases, we do not allow for this difference in the rising and falling stages in our flow-rating curves though they must actually be different.

The writer has endeavored to get some examples of this method of computing storage in the main river-channel by taking as inflow the known discharge from power-stations and as outflow the hydrographs taken at gaging-stations some miles downstream. The storage-curve was then determined from the recession-curve of the gaging-station hydrograph and the storage applied to the power-station discharge, that is the inflow-hydrograph, the general storage-equation being used for both rising and falling stages.

The storage-curve in all cases is figured using the base-flow as inflow and the hydrograph recession-curve as outflow. This gives zero-storage at the base-flow at the end of the "flood" The curve is then extended by eye down to zero-flow and the storage-values increased by the additional storage from the base-flow to zero-flow. This storage-curve can then be used for all flows.

The volume of the "inflow" from the power-station required some adjustment to give a total runoff-volume above the base-flow equivalent to that of the hydrograph at the gaging-station. Also, except in one case, the vertical rise in flow between different hours of the power-station discharge was inclined slightly so that the storage-equation could be applied without qualification. This assumption does no violence to the data as the power-station discharges are given by the hour and thus may vary during an hour. The power-station discharges were obtained through the kindness of the New England Power Company and the Public Service Company of New Hampshire, and the gaging-station hydrographs from the District Office of the United States Geological Survey.

In each case the inflow (power-station) hydrograph is moved to the right by an allowance for time of transit sufficient to bring the computed and actual recession-curve in synchronism. In each of the Figures, the curves numbered 1 and 2 are the actual hydrographs of the power-station discharge and at the gaging-station downstream. Curve 3 is the power-station discharge (inflow) adjusted to give equal "flood" runoff-volume and moved to allow for the time of transit. Curve 4 is the outflow-hydrograph computed from curve 3 using the storage figured from the recession-curve.

The first case, shown on Figure 6, is on the Deerfield River. In this case the inflow-hydrograph was simplified. It will be noted that the rising limb does not follow the actual hydrograph and the peak-flow is about ten per cent smaller than the actual hydrograph. This, however, is a very extreme case. Before the discharge from the power-station starts there is practically an empty river with a flow of 0.108 csm and then a sudden rise up to over 1,000 cfs, or nearly 2.0 csm. There is no storage except that in the river-channel in the 3-1/2 miles between the power-station and the gaging-station.

Figure 7 shows the record of a gaging-station on the Merrimac River which is located 5-1/4 miles below the two generating stations--one a small one on a branch stream, but here also there is no storage except the river itself. The base-flow is somewhat greater than in the previous case though it is still a small flow for the river, approximately 0.20 csm. The computed hydrograph

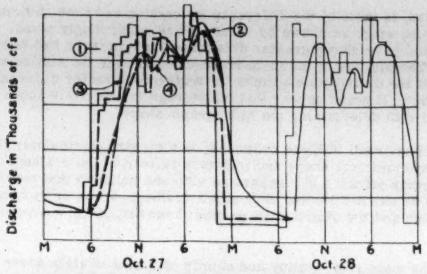


Fig. 7--Flow of Merrimac River at Goffs' Falls (3092 sm) and discharge from Amoskeag and Kelleys' Falls plants of the Public Service Company of New Hampshire

shows a much better fit with the actual hydrograph than in the previous case. This is probably due to a somewhat larger initial storage in the river-channel.

The third case, shown on Figure 8, is on the Winnepesauke River in New Hampshire. The gaging-station is at Tilton, 4-1/2 miles downstream from the Lochmere Plant of the Public Service Company of New Hampshire. There is considerable natural storage in this stretch of river and one small mill-pond, now not used. It appears to be due to this storage that the actual and computed hydrographs are more nearly the same than in the previous two cases.

In these examples the difference between the actual rise and the computed rise, using the curve of recession-storage, is greater the lower the river-stage at which the rise begins and apparently the difference in time of transit down the river between the rising and falling limbs of the hydrograph is also greater, as would be expected. In these cases the difference between the

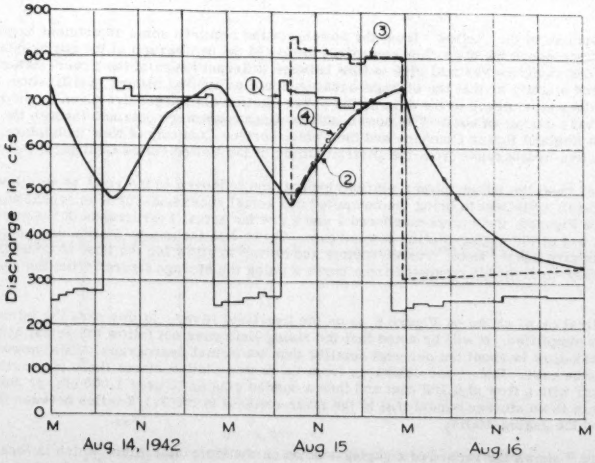


Fig. 8--Flow of Winnipesauke River at Tilton, New Hampshire, and discharge from Lochmere Plant, Public Service Company of New Hampshire

rising and falling stages is greater at periods of really low flow than at higher stages. This is the condition at the first part of a flood. Here the effect of the storage is not generally so important and there are many other factors difficult to assess at the very start of any flood-rise.

When the differences in storm-rainfall over many square miles of area with different kinds of soil, vegetation, and slopes are considered, it seems extraordinary that we get such uniform flood-hydrographs that the unit-hydrograph and distribution-graph can be used at all. The uniformity of the recession-curves is also extraordinary when one considers the varied conditions of the source of this flow from storage during different floods. The writer believes that the storage in the main river-channel--chiefly that near the station--is the chief factor in ironing out the differences in the various floods to produce this uniformity. If this is so, the behavior of channel-storage should permit without much error, in most cases, applying to the rising stage the storage determined from the recession-curve. There will be some difference caused by the changing slope in the two cases but the writer believes that it is sufficiently accurate for the purpose to use the storage-curve as was done in this paper.

References

[1] H. K. BARROWS, A study of valley-storage and its effect on the flood-hydrograph, Trans. Amer. Geophys. Union, p. 483, 1942.
[2] H. M. TURNER and ALLEN J. BURDOIN, The flood hydrograph, J. Boston Soc. Civ. Eng., p. 232, July, 1941.
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DISCUSSION

WILLIAM T. COLLINS (Huntington, West Virginia)--Mr. Turner's basic concept that storage can be determined from the recession-side of a hydrograph is generally accepted. If reasonable estimates of base-flow are made, the volumes of storage will approximate true values at the instants for which the determinations are made. It is logical to assume, as did the author and Professor Barrows, that it can be used in analysis to determine the channel-inflow into the basin. Both authors have assumed that the same relation between outflow and storage exists during rising stages as during the recession. As WALDO E. SMITH pointed out in discussion, this introduces considerable error. The author recognizes the existence of the hysteresis-effect in the storage-outflow relation but continues to neglect it presuming it to be small.

Within a reach of unit-length, storage can be related to the stage, and in most cases to discharge, without any hysteresis-effect. The storage which affects the outflow-hydrograph of a drainage-basin is the integration of the storage in all of the unit-reaches. When it is considered that crests occur upstream before they occur at the outflow-station, it is evident that there will be a hysteresis-effect if an attempt is made to relate the total storage to any one gage whether it be at the outlet or near the middle of the reach, as has sometimes been suggested. Mr. Turner assumes that the hysteresis-effect is of the same order as the change of the rating of a discharge-station on rising and falling stages, that is, just a few per cent. Consider a rectangular channel 100 feet wide with a normal slope, equal to the slope of the stream-bed, of one foot per 100 feet and the water ten feet deep at the outflow-station. If during rising stages the slope is five per cent greater than normal, that is, 1.05 feet per 100 feet, the discharge would be less than five per cent greater than normal, since velocity varies with the square root of slope. Between 1,000 and 1,100 feet upstream from the gage the storage would be 105,250 cubic feet which is 5-1/4 per cent greater than normal. Between 10,000 and 10,100 feet above the gage the storage would be 150,250 cubic feet, 50-1/4 per cent above normal and 25-1/4 per cent greater in the reach up to this point. If computations of this nature were carried out for the Delaware River above Port Jervis, New York, which is about 100 miles long and it were assumed that the crest was about half-way down the reach, it can be seen that the volume of storage would be tremendously greater than for normal slopes. During falling stages there is never as great a variation from normal slope as during rising stages, so there is not such a great difference from normal in the volume of storage. HORTON, to whom the authors ascribe the principle upon which the method is based, has said [see 1 of "References" at end of discussion] "The channel-storage outflow-rate relation for receding stages . . . . . cannot be applied to rising stream-stages." Mr. Turner has assumed that "The storage in the rising stage should not be very different from that in the falling stage."

Attention is invited to Mr. Horton's storage-loop for the Delaware River above Port Jervis, New York [2]. It shows that storage during rising stages is as much as 4,600 per cent of that for the same discharge during recession. Curvature of the storage-relation cannot be neglected. The example for the Delaware River has been recomputed by the writer, following the methods of both Professor Barrows and Mr. Turner exactly, except that the two higher points which Professor Barrows computed, but did not use, were plotted and the curvature which they indicate was taken into account. Values of the peak-inflow so computed were 152,000 cfs and 190,000 cfs, which are to be compared, respectively, with 242,000 cfs and 267,000 cfs as computed by the authors using a straight-line storage-relation. These figures are not given as better values of the peak-rate of channel-inflow, but are mentioned to show the amount of error, approximately 50 per cent in this case, which can be introduced by neglecting an apparently slight curvature in any storage-discharge relation.

Hourly precipitation-records for September, 1938, for three recording gages on the drainage-area of the Delaware River above Port Jervis, New York, and for two adjacent to it have been obtained from a publication [3] of the Muskingum Climatic Research Center. The heaviest rainfall was from 09^h to 20^h, September 21, 1938, and all precipitation had ceased by 23^h of that day. Light rain resumed at 22^h, September 22, 1938. A varying infiltration-capacity with f_c as 0.07 inch per hour was assumed and one hour was allowed as the concentration-time for overland flow to reach stream-channels. The concentration-time of overland flow was not applied as a lag, but was applied by routing the excess of rainfall through enough storage to delay its center of mass one hour, which caused the end of the overland flow to be delayed until two hours after the end of excess of precipitation. Based on these approximations, significant points on the channel-inflow hydrograph are given below.

Date	Time	cfs
	h m	
September 20, 1938	17 00	4,000*
	18 00	131,000
	20 30	78,000
	21 30	112,000
	24 00	4,000*
September 21, 1938	03 00	5,000*
	04 30	20,000
	06 00	5,000*
	09 00	5,000*
	12 30	168,000
	16 00	534,000
	20 00	60,000
	22 00	5,000*
September 22, 1938	24 00	6,000*
September 23, 1938	02 00	39,000
	04 00	6,000*

*Beginnings and endings of surface-flow equal to base-flow.

The authors' method is an attempt to institute a procedure whereby the validity of the approximations in the foregoing could be checked. Therefore, the channel-inflow determined from records of precipitation is not intended to be substituted for that derived by their method. However, the approximations used above are reasonable enough so that this hydrograph can be used for comparison with the authors'. There is no similarity between the two, due chiefly to neglect of the hysteresis-effect in the storage-relation. The extent of the hysteresis can be shown by comparing the storage-values at 21^h, September 21, 1938, assuming the hydrograph derived from rainfall to be correct--this is the time of maximum storage and its amount is 158,000 dfs, whereas that derived from the outflow-storage relation, as calculated by the authors, is 51,000 dsf. These figures compare reasonably well with the values on the two branches of Horton's curve referred to above. The storage at the time of crest-outflow, which in the authors' method appears to be the maximum, was 114,000 dsf. If the method gives as great errors in the apparent maximum storage for the Connecticut River as for the Delaware River, Mr. Turner's comparison with storage measured by the Providence Office of the United States Engineers will need to be revised.

The only possibility of utilizing channel-storage to determine the channel-inflow hydrograph from the outflow-hydrograph is by successive approximation. It would be necessary to decide in advance how many steps would be used in the analysis, and the number would probably depend upon the size of the drainage-basin. Suppose ten steps were to be used. In the first step only one-tenth of the storage would be utilized. From the recession of the hydrograph so determined a new storage-curve would be drawn and one-ninth of the storage used. Successive steps would be carried out similarly using 1/8, 1/7, 1/6, 1/5, 1/4, 1/3, 1/2, and finally all of the storage determined from the successive hydrographs. The one found by using all of the storage would be the channel-inflow. The number of steps necessary in such a method can be reduced considerably if some approximation of the hysteresis-effect is introduced into the storage-discharge relation.

Mr. Turner's examples using the outflow of power-stations as inflow to the reach are much simpler cases than the problem considered by Professor Barrows. On the Deerfield River only the lower 3-1/2 miles of a river draining 588 square miles, on the Merrimac River 5-1/4 miles at the lower end of a drainage-basin of 3,092 square miles, and of the 471 square miles of the

Winnepesauke River above Tilton, New Hampshire, only the lower 4-1/2 miles of main stream were considered. The fact that Mr. Turner had to make arbitrary adjustments in the time of the inflow in these examples, where all the inflow occurred at a point and where the storage was all in one short reach, resulted from neglect of hysteresis in the storage-relation and shows clearly that the method as it stands can not be applied to the more complicated cases where inflow is occurring simultaneously all over the basin and where storage takes place in many tributaries.

References

[1] ROBERT E. HORTON, Natural stream channel-storage, Trans. Amer. Geophys. Union, p. 440, 1937.

[2] ROBERT E. HORTON, Flood-crest reduction by channel-storage, Trans. Amer. Geophys. Union, p. 820, 1941.

[3] Hourly precipitation on the upper Ohio and Susquehanna drainage basins for the month of September 1938, Muskingum Climatic Res. Center, SCS-PC-9, September, 1941.

HOWARD M. TURNER--Mr. Collins' discussion appears to assume that the writer's paper approved of Professor Barrows' inflow-hydrograph which he refers to as being the writer's, as well as that of Professor Barrows. On the contrary the writer stated that he disagreed with Professor Barrows' computations in all respects except his basic assumption. He noted objections to Professor Barrows' figures for the Delaware River at Port Jervis including the storage-curve, the use of intervals of 10,000 second-feet and gave his conclusions that the actual flood-hydrograph cannot be used to give determinate results of the inflow-hydrograph. The only part of Professor Barrows' method of which the writer approved was the basic assumption of the use of the storage-curve determined from the recession-side of a hydrograph for computations involving the storage in the rising limb.

Mr. Collins cites, as an example against this assumption, the hysteresis-effect of the storage-curves for rising and falling flows, a rectangular channel 100 feet wide and ten feet deep carried out for the 100-mile length of the Delaware River above Port Jervis and points out that computations on this basis would show large differences in the storage of the rising stage and the falling stage. The writer does not dispute the result which might be obtained with these assumptions but considers them so far from the actual storage of the Delaware River effective at Port Jervis as computed from the recession-curve that such a computation would scarcely be worth while.

Mr. Collins also calls attention to Dr. Horton's storage-loop for the Delaware River above Port Jervis [see 1 of "References" at end of discussion]. This is not the place to enter into a discussion of Dr. Horton's virtual inflow-hydrograph on which this is based [2]. This virtual hydrograph from which his storage-curves are determined is triangular in shape and assumed under requirements which will permit of considerable latitude with consequent variation in the channel-storage. The storage he shows in this case is affected also by the assumption regarding a large flow from ground-water during the recession which if different would materially change the storage-results.

The author of the discussion gives in tabular form his own inflow-hydrograph and uses it to verify Dr. Horton's storage-curves. This inflow-hydrograph does not fulfill any of the requirements of an inflow-hydrograph. Its total runoff-volume is considerably less than the total flood-runoff. The principle that outflow- and inflow-hydrographs intersect at the point of maximum outflow is entirely neglected, most of the flow occurring over 14 hours before the crest of the flood.

Mr. Collins describes briefly a method of determining the hydrograph of channel-inflow from the outflow-hydrograph by successive approximations. The writer has not had an opportunity to study and apply this but if Mr. Collins has discovered a method of doing this satisfactorily it is to be hoped that he will develop it further.

The writer has derived an inflow-hydrograph for the Delaware River at Port Jervis by his own method as outlined in a previous paper [3] and briefly described in this one. This inflow-hydrograph is a rational one based upon (1) a total runoff-volume above the base-flow equal to the actual flood-flow, (2) the duration of the storm-rainfall, (3) the time required for the rainfall from the farthest portion of the watershed to reach the station (that is, the concentration-period), and (4) fulfillment of the time-requirements of the outflow-hydrograph. If the rainfall is assumed steady such a hydrograph will be a triangle or trapezoid, depending upon the relation between the duration of the storm and the concentration-period. In this particular case the writer has adjusted this inflow-hydrograph, by the same methods, to allow forlthe fact that rainfall was at a great deal lower rate during the first half of the storm than in the latter part. Using the storage-curve as shown derived

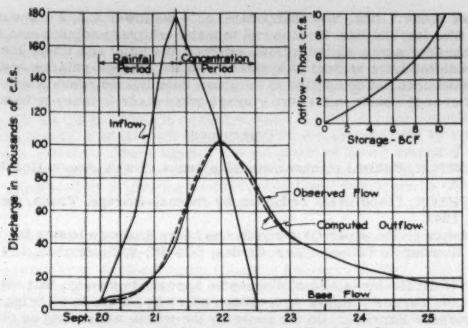

Fig. A--Delaware River at Port Jervis, flood of September 1938

from the recession-curve the outflow-hydrograph has been computed as shown by the dotted line on Figure A compared to the actual hydrograph; the peak of the inflow is 178,000 cfs.

Mr. Collins states that the writer has made arbitrary adjustments in the time of inflow of the examples he gives of channel-storage. Each of these examples was based on two actual hydrographs. The time required for the discharge at the upper station to pass downstream to the lower was a matter of recorded fact. The time-lag of the initial rise at the lower station, in some cases was slightly different from the lag of the break at the beginning of the recession. The computed hydrograph from the storage-curve would have the same values in any event. In plotting this figured curve to compare with the actual one, a selection had to be made as to the time-lag used. It was chosen to do this using the recession-side where the actual and figured curves were the same.

The question has yet to be answered as to how it is possible, using any such computations as Mr. Collins suggests in his own hydrograph, to have the uniformity shown by the unit-graphs and distribution-graphs for all floods. Recession-curves correctly figured are all substantially similar. The system proposed by Mr. Collins would make a great variation in the rising limb for different floods. The writer points out that the reaches immediately above the station may be the determining factor in the relation between outflow and storage, which would account for the uniformity of the flood-hydrographs for different floods with different rainfall-distributions. In this case the hysteresis-effect will be small as is the case in a single reach and the storage on both sides of the hydrograph will be substantially the same.

References

[1] ROBERT E. HORTON, Flood-crest reduction by channel-storage, Trans. Amer. Geophys. Union, p. 820, 1941.

[2] ROBERT E. HORTON, Virtual channel-inflow graphs, Trans. Amer. Geophys. Union, p. 811, 1941.

[3] H. M. TURNER and ALLEN J. BURDOIN, The flood hydrograph, J. Boston Soc. Civ. Eng., p. 232, July, 1941.

STATISTICAL CONTROL OF HYDROLOGIC DATA FROM EXPERIMENTAL WATERSHEDS

H. G. Wilm

As a part of numerous hydrologic studies in this country and elsewhere, intensive experiments have been undertaken to determine the influence of timber-cutting or other changes in plant-cover or land-use upon water-yields, flood-flows, erosion, and related factors. In these studies, ordinarily two or more watersheds are subjected to control by means of stream-gaging stations, rain-

gages, snow-courses, and similar equipment. Records of stream-flow and precipitation are obtained from each watershed over a period of years, and then the desired treatments are applied to some of the areas, while one or more is kept untreated as a check. Records taken after treatment for another period of years are analyzed to determine the influence of the treatment or treatments upon water-yield and other factors.

Complicating this simple procedure are a number of extraneous factors which may obscure the real influence of the treatment. Of these, perhaps the most important are changes in precipitation and related factors in the period after treatment as compared to the "calibration" or pre-treatment period, which result in substantial changes in water-yield entirely aside from any effects of the treatment. Such changes are, of course, reflected in yields derived from untreated watersheds, as well as in precipitation-data obtained for all of the experimental watersheds. In the analysis and interpretation of results, however, it is not always simple to utilize this check-information in a completely unbiased manner, so as to isolate the influence of climatic changes and reveal the true influence of the treatments. Conclusions have often been drawn simply from inspection of a rather complex mass of data, or graphical analyses have been employed to estimate "normal" water-yields from the treated area or areas.

Both inspection and graphic methods are exposed to the risk of error or bias because they require a large element of judgment, and the latter may become so complex and require so many approximations that the investigator may even question his own interpretation of the results. Thus it is desirable to employ some analytic method which is straightforward and rigorous in its procedures, and which expresses the treatment effects quantitatively and as far as possible free from the effects of extraneous factors.

In this paper a method is outlined that satisfies these requirements. It has won general use in biological research, and seems equally well suited to hydrologic investigations. Starting with the hypothesis that there exists no real influence of timber-cutting on the water-yield from a controlled area, the method proceeds to test this hypothesis by mathematical analysis, removing to a large extent the influence of climatic changes on yields from the treated watershed. In the following sample case the problem is presented in its simplest form, with discharge from a contiguous untreated watershed serving as the only climatic control on yields from the treated area. The method may be expanded to include additional climatic variables and, if desired, treatment of more than one watershed. No attempt is made to outline in detail the algebraic aspects of the method, as they are adequately discussed in various texts [see 1,2 of "References" at end of paper].

The sample case

General--

Problem: To determine the net influence of timber-cutting on water-yields from a forested watershed.

Given: (1) Hydrographs from Watershed A, for a five-year period before timber-cutting and a similar period after cutting.
(2) Hydrographs from Watershed B for ten years concurrent with data from Watershed A; B untreated throughout the period.

Basic assumptions: (1) Both before and after treatment the water-yield from Watershed A is correlated with yield from Watershed B.
(2) Variations in annual yield from Watershed B reflect changes in precipitation and other climatic factors which also affect yields from Watershed A.

In this example only total annual water-yields from snow are analyzed. A similar procedure may be employed to study the effect of timber-cutting on yield from rain, or on the total yield from all three sources.

Procedure--

Hydrograph analysis: On each year's hydrograph for each watershed, segregate runoff due to snow-melt from base-flow and from runoff due to rain; calculate the volume, in acre-feet, of water appearing as discharge from snow for each year. In subsequent analyses, each runoff-figure for Watershed A will provide a single number for the dependent variable; corresponding data for Watershed B will provide figures for the independent variable.

The basic data: In Table 1 are listed hypothetical annual discharges from snow, in acre-feet, for watersheds A and B; these data were set up with three assumptions:

Table 1--Annual discharges from snow, watersheds A and B

Year	Discharge, acre-feet	
	Watershed B	Watershed A
	(X)	(Y)
	(1) Before treatment	
1940	950	540
1941	1050	650
1942	540	380
1943	1200	780
1944	780	590
Sum (SX, SY)	4520	2940
Mean ($\bar{x}_1$, $\bar{y}_1$)	904.0	588.0
	(2) After treatment	
1946	580	690
1947	250	360
1948	710	700
1949	920	850
1950	550	520
Sum (SX, SY)	3010	3120
Mean ($\bar{x}_2$, $\bar{y}_2$)	602.0	624.0
Grand sum	7530	6060

(1) For each annual discharge from Watershed A there is a corresponding discharge from B which, because the two watersheds are contiguous, is more or less strongly correlated with the figures for A.

(2) The net effect of timber-cutting is to increase discharges from Watershed A.

(3) This effect, in the two five-year periods studied, is partly obscured by a downward change in climatic factors inducing runoff. The effect appears in two ways: Discharge from Watershed A is not greatly increased in the period subsequent to treatment; and discharge from the continuously untreated Watershed B is lower in the second period than in the first.

Statistical analysis: The runoff-data for the periods before and after treatment are plotted on coordinate paper (see Fig. 1), with discharge from Watershed B as abscissa and Watershed A as ordinate. From this chart it appears that both trends can be expressed by straight lines.

These data are analyzed by the covariance-method (Table 2). As used here, the method involves fitting a straight line by least squares to each of the two trends [2]. Then (as a part of the analysis) the mean discharges from Watershed A before and after treatment are adjusted to the values which would be expected if discharge from Watershed B had been identical in both periods; and the difference between these adjusted discharges is tested for its significance. Also, the slopes of the two lines may be tested to see if they differ significantly.

Table 2--Analysis of covariance: Effect of timber-cutting on water yield from watershed A, adjusted to mean yield from watershed B

Line	Source	Degrees of freedom	Corrected squares and products			r^2[a]	b[b]	Degrees of freedom	Errors of estimate	
			Sx^2	Sxy	Sy^2				Sum of squares[c]	Mean square
(1)	Total	9	726,810	288,920	231,240	.496,674	.....	8	116,389.1	14,548.6
(2)	Periods	1	228,010	- 27,180	3,240	.....	.....	1	88,708.3	88,708.3[d]
(3)	Error, (1) - (2) (within periods)	8	498,800	316,100	228,000	.878,592	.6337	7	27,680.8	3,954.4
(4)	Period 1	4	258,920	139,140	86,280	.866,619	.5374	3	11,508.1	.....
(5)	Period 2	4	239,880	176,960	141,720	.921,139	.7377	3	11,176.2	.....
(6)	Sum, [(4) + (5)]	..	498,800	316,100	228,000	.....	.....	6	22,684.3	3,780.7
(7)	Within periods, (3)	..	498,800	316,100	228,000	.....	.....	7	27,680.8	.....
(8)	Diff. [(7) - (6)]	..	.....	.....	.....	.....	.....	1	4,996.5	4,996.5[e]

[a] $r^2 = [(Sxy)^2/(Sx^2)(Sy^2)]$ = squared correlation-coefficient. [b] $b = [Sxy/Sx^2]$ = regression-coefficient. [c] Sum of squares = $\{Sy^2 - [(Sxy)^2/Sx^2]\}$. [d] Treatment significant; odds less than 0.01 that the difference between periods is due to chance alone. [e] Not significant.

Both trends may be expressed by linear equations of the form $E = \bar{y} + b(X - \bar{x})$, or $E = a + bX$ [1,2]. For the period before treatment, the equation is

$$E_1 = 102.20 + 0.5374X \quad (1)$$

After treatment, it is

$$E_2 = 179.90 + 0.7377X \quad (2)$$

In both equations (1) and (2) E = estimated discharge from Watershed A, and X = measured discharge from B.

In lines (6) to (8) of Table 2, a test of the two regression-coefficients (0.5374 and 0.7377) is presented, showing that the difference between them is no greater than might be expected by chance. Accordingly, the best estimate of the slope of both lines is the weighted mean of the two coefficients. This means that the two equations may more safely be expressed as

$$Y_1 = 15.117 + 0.6337X \quad (1)$$

$$Y_2 = 242.501 + 0.6337X \quad (2)$$

These two regression-lines are shown in Figure 1. In this chart the unadjusted mean discharges for Watershed A, corresponding to the observed mean discharges for Watershed B, are shown by the horizontal dashed and dotted lines (588 acre-feet before, and 624 after treatment). If Watershed B had remained constant, the discharges which would have been expected from A can be ob-

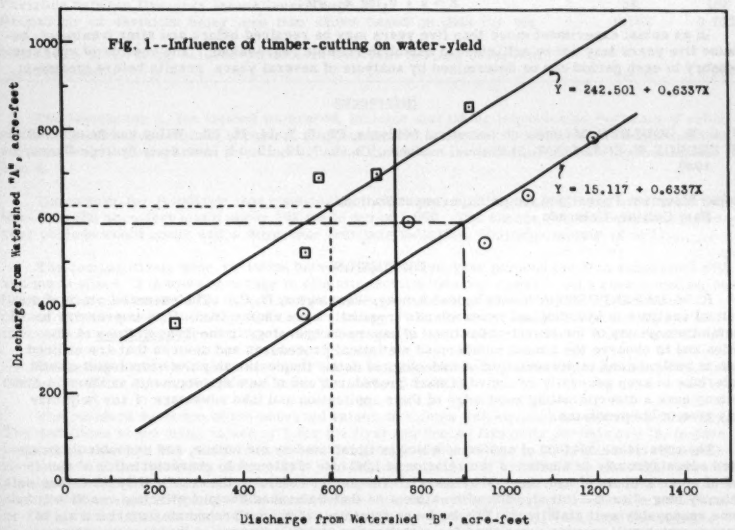

Fig. 1--Influence of timber-cutting on water-yield

tained either graphically or mathematically. Graphically, the ten-year mean discharge from B is plotted as a vertical solid line (at 753 acre-feet on the abscissa); the adjusted discharges from Watershed A are read from the intersections of this line with the two regression-lines. Obviously the same result can be obtained with greater precision by solution of the two equations, namely

$$E_1 = 15.117 + (0.6337)\ (753) = 492.3 \quad (1)$$

$$E_2 = 242.501 + (0.6337)\ (753) = 719.7 \quad (2)$$

In the column "Mean square, errors of estimate", in Table 2, the difference between these adjusted yields is shown to be much greater than any difference which might have occurred by chance. Where F is the ratio of adjusted "Period" mean square (errors of estimate) to "Error" mean square [2], F = (88,708.3/3954.4) = 22.43 and odds are less than 1 in 100 that the difference is due only to chance variation. Thus timber-cutting is shown to have had a real effect on water-yields from Watershed A.

This example is, of course, only suggestive, and presents only a simple and common sample of many possible cases. The method can often be increased in precision by adding more independent variables, each of which is not itself associated with the treatment but does express climatic variations. Such an analysis soon becomes impossible to handle graphically, but can be done mathematically with little increase in complexity. For three independent variables, each in a linear-regression, the equations take the form

$$E = a + b_1x_1 + b_2x_2 + b_3x_3$$

in which each b expresses the net effect of each independent variable, with the others held constant. If any of the variables is best expressed by a curve, the above equation may be varied to suit the type of curve involved. Thus for a parabola

$$E = a + b_1x_1 + c_1x_1^2 + b_2x_2, \text{ etc.}$$

or for a logarithmic function

$$E = a + b_1 \log x_1, \text{ etc.}$$

In an actual experiment more than five years may be required before and after treatment, because five years may not be sufficient to establish reliable regressions. The number of years necessary in each period can be determined by analysis of several years' results before treatment.

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[1] C. H. GOULDEN, Methods of statistical analysis, Ch. 6, 7, 14, 15, John Wiley and Sons, 1939.
[2] GEORGE W. SNEDECOR, Statistical methods, Ch. 6, 7, 12, 13, 14, Iowa State College Press, 1940.

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DISCUSSION

R. W. DAVENPORT (U. S. Geological Survey, Washington, D. C.)--The essential place of statistical analysis in hydrological research has frequently been emphasized. It is impressive to thumb through any of the recent collections of papers on hydrology in the Transactions of this Union and to observe the almost numberless statistical procedures and devices that are utilized both in analysis and in presentation of hydrological data. Unquestionably the hydrologist should undertake to keep generally informed of such procedures and of new developments in them so that he may have a discriminating knowledge of their application and take advantage of any help they may give in his problems.

The covariance-method of analysis, which is illustrated by the author, can undoubtedly be applied advantageously in studies of the relation of land-use treatment to characteristics of runoff and of other aspects of hydrological research. The author refers to the desirability of waiting sufficiently long after the introduction of treatment so that watershed-factors affecting runoff will become reasonably well stabilized. The land-use treatment of the watershed may start a train of changes which will require some time for stabilization and it is important that any experimental data obtained during that period shall be viewed with due regard to their possible transitional character.

There are often questions as to whether hydrological data involve cyclic tendencies, possibly associated with climate, or complex interdependencies which may invalidate to some extent the application of methods which presume conformity with a normal or other definite frequency-distribution. This aspect should be kept in mind in making and interpreting the results of statistical analysis.

There are other statistical processes which might be applied to the data to develop their characteristics and to test whether the effects of timber-cutting are significant. The coefficients of variation have been computed for the discharge-data of Table 1 for the individual five years before and after treatment and for the combined ten-year periods. A summary of the results follows.

Watershed	1940-44		1946-50		1940-44 and 1946-50	
	Mean discharge, acre-feet	C V	Mean discharge, acre-feet	C V	Mean discharge, acre-feet	C V
A	588	0.250	624	0.304	606	0.265
B	904	0.282	602	0.406	753	0.380

The probabilities of deviations by five-year means of the magnitudes indicated may be computed on the basis that the variation-characteristics of the population are represented by the ten years of experimental data. Likewise the probability of deviations between successive five-year means of the magnitudes indicated may be computed on the basis of the characteristics displayed by the ten years of experimental data. The results are given below.

Item	Watershed	
	A	B
Variation between five-year means (acre-feet)	36	302
Probability of deviation being less than shown based on data for ten years	0.197	0.762
Probability of deviation between successive five-year periods being less than shown	0.268	0.907

The results for A, the treated watershed, indicate that taking ten years as the basis of reference, a deviation less than 36 acre-feet might occur 197 times out of 1,000. The chance that two successive five-year periods would occur with a difference less than indicated is approximately 1 in 4.

The results for B indicate that considering the ten years as the basis of reference, a deviation less than 302 acre-feet might occur 762 times out of 1,000. The chance that two successive five-year periods would occur with a difference less than indicated, is approximately 10 in 11.

The comparatively wide variation between the two five-year periods for B is associated with and may reflect "a downward change in climatic factors inducing runoff". Any corresponding reflection of such change in the runoff of A is apparently obscured either by the peculiarities of chance variation or by the effects of timber-cutting. What is the probability that the characteristics of correlation presented, can be explained wholly by the peculiarities of chance variation?

It may be assumed that all the observations are represented by the same equation which, from the data in Table 2, is readily found to be $Y = (307 + 0.397X)$.

The standard deviation of the observed values of Y from this equation is computed to be 114. The deviations of the mean values of Y for the first and second five-year periods are 78, in each instance of course. The standard deviation for groups of five values is $(114/\sqrt{5}) = 51$. The relative deviate of the five-year mean, $(78/51) = 1.53$, corresponds to a probability of 0.126. There is a chance of 1 in 8 that deviations for five-year periods would be greater than shown. However, the chance that random sampling-differences between averages of successive five-year periods would be 156, is less. The standard deviation of such differences is $\sqrt{51^2 + 51^2} = 72$ and the relative deviate 2.17, which corresponds to a probability of 0.030. Thus there is a chance of 1 in 33 that the deviations equal to or greater than indicated may have resulted from chance variations, which practically excludes that hypothesis and supports the author's conclusion that timber-cutting had a real effect on water-yields.

It is interesting to explore the condition that the regression-lines may pass through the origin. The equation for the 10-year period is $Y = 0.805X$. The standard deviation of observed values of Y from this equation is 163. The deviation of the mean values of Y for the first and second five-year periods is 140. The standard deviation for groups of five values is 73. Therefore, the relative deviate is 1.92, corresponding to a probability of 0.055. This indicates a chance of 1 in 18 that deviations for five-year periods might be greater than shown. The odds for the indicated differences between averages of successive five-year periods are 1 in 154.

The results support the author's conclusion and the rather obvious visual interpretation of Figure 1, that timber-cutting had a real effect on water-yields from Watershed A. Nevertheless, the example illustrates that a sharp variation in runoff-behavior during the period of an experiment

might obscure or invalidate evidence on the question investigated, particularly if the effect of treatment is rather small in relation to other variables.

The author conducts his analysis on the assumption that timber-cutting is effective and that the two five-year periods are represented by two distinctive equations. He computes the regression-coefficients of these equations to be 0.5374 and 0.7377, and applies a test which shows that the difference between them is no greater than might be expected by chance. He concludes that the best estimate of the slope of both lines is the weighted mean of the two coefficients, 0.6337. This conclusion seems to rest on the assumption that the effect of timber-cutting, if any, is to increase the water-yield from snow-melt runoff by a constant amount each year, irrespective of the varying quantities of snow. It seems to the writer that such effect would be more likely to vary in some degree with the quantity of snow from year to year. Apparently the immediate problem considered by the author is whether timber-cutting is effective. A possible criticism of the illustrative application of the covariance-method is the assumption made as to the character and magnitude of the effect. Such details concerning the effect constitute a further statistical problem which is not disposed of in this example.

A SYSTEM FOR THE SYNCHRONIZATION OF HYDROLOGIC RECORDS

E. L. Hamilton

"The moving finger writes and having writ, moves on." Omar, the Tentmaker, who wrote these words many years ago, probably was never plagued by recording instruments that, "having writ"--move on at a different rate of speed. On the San Dimas Experimental Forest [C. J. KRAEBEL and J. D. SINCLAIR, The San Dimas Experimental Forest, Trans. Amer. Geophys. Union, pp. 84-92, 1940] in southern California, however, essential measures of rainfall-intensity, stream-flow, temperature, and other variables must be made through the medium of automatic recording-instruments. Of necessity, these instruments are clock-driven and the excellence of the records obtained is directly proportional to the time the individual clocks keep. The watershed-management studies that have been under way since 1933 at this branch of the California Forest and Range Experiment Station involve hydrologic measurements from some 26 square miles of chaparral-covered watersheds (Fig. 1). These investigations are dependent to great measure upon records from 13 intensity rain-gages, 43 water-stage recorders, eight hygrothermographs, seven soil-thermographs, one barograph, and ten strip-chart recorders, a total of 82 separate clock-driven instruments; and it must be added that 19 separate functions may be recorded on each strip-chart recorder.

Clocks do not keep accurate time all the time; some of them none of the time, as was probably noted by Alfred the Great when one of his calibrated candles burned down to an oleo-stearic stratum of a different flash-point from that of the original model. The observer also may be at fault and, while having the best of intentions, may even confuse Monday with Tuesday in his entry on the chart. A single drop of water falling with diabolical precision on the chart may throw the whole calendar out of sequence. The backlash of gears may disrupt the rising or setting of the Sun, and friction-clutches may institute daylight-saving time without benefit of Congress. The investigator having struggled manfully with such obstacles and refusing to believe that a heavy rain on Thursday, February 18, caused the peak-flow in Bell Canyon No. 3 on Wednesday, February 17, devised a system to synchronize the essential, widely scattered, and recalcitrant clocks on this research-project.

Recorder-synchronizing system--The recorder-synchronizer as finally worked out is presented diagrammatically in Figure 2. It consists of a master-clock located centrally in the laboratory at the Tanbark Flat field-headquarters of the experimental forest. This timepiece, which is similar to those used to ring the class-period bells in schools, sends out an electric impulse hourly through a master-relay. The impulse is conveyed by separate grounded circuits hung with the telephone-circuits to various relay-centers--usually shelter-cabins located within convenient reach of several recording instruments. The time-impulse here operates a sensitive relay, which in turn causes a magnet-actuated pen mounted on the recorder in question to make a mark on the margin of the chart. Consequently, all the instruments so equipped will bear an identical pattern of time-marks. The clock of an individual recorder may run fast or slow, but so long as it continues to run the operation or function it delineates will be chronologically in step with all the others. The impulses are differentiated at noon and at midnight, so that there can be no confusion within a 12-hour period.

The clock--The key member of the synchronizing system is of course the master-clock. This is a five-minute interval adjustable program clock (Fig. 3-A). It has a pendulum-regulated, self-

winding movement, and is so equipped that it can readily be fitted with a standard Western Union hourly time-correction mechanism. The service supplied by Western Union would be welcome; but since circuits are not available to bring it to the isolated mountain location of the clock, dependence must be placed on manual correction according to radio time-signals, an operation that is necessary only at infrequent intervals. The clock is driven by a spring which is rewound at regular hourly intervals as an electric contact is made whereby an interrupted electromagnet actuates a ratchet- and pawl-mechanism. Power for its operation at six volts direct-current is supplied through a dry-disc rectifier or from suitable dry-batteries. Since power-lines are subject to interruptions of service, especially during storm-periods, ordinary dry-cells are used in all phases of the operation of this system.

In the lower portion of the clock is the program-disc, which has a slot in its edge for each five-minute period of the day. Contact-clips are inserted in these slots according to the schedule

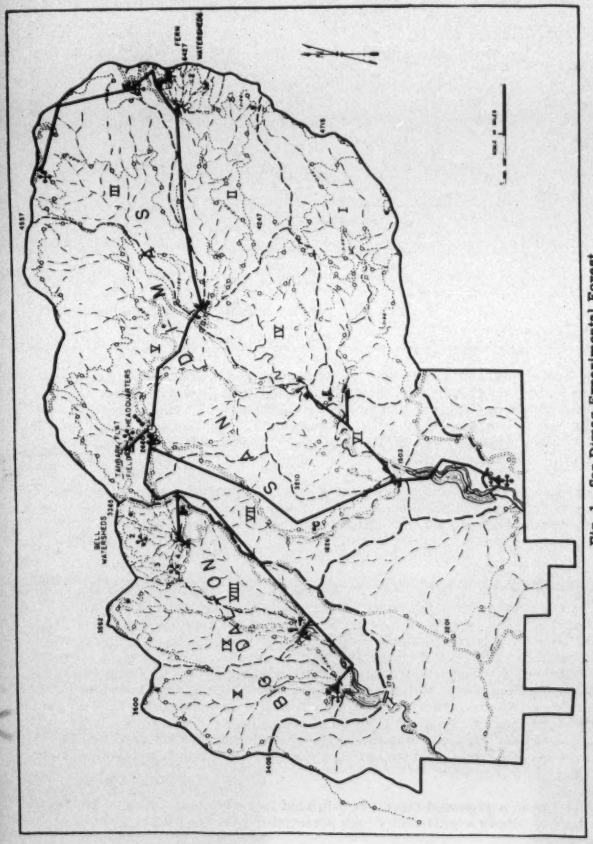


Fig. 1.--San Dimas Experimental Forest

LEGEND

- Synchronizer transmission-lines
- Synchronizer relays
- Master clock
- Forest boundary
- Watershed boundaries
- Major watershed
- Bell-Fern watersheds
- Stream gaging-station
- Streams
- Trails
- Roads
- Extensive rain-gage
- Intensity rain-gage
- Climatic station
- Runoff-erosion plot
- Dams
- Elevation
- Lysimeters
- Buildings

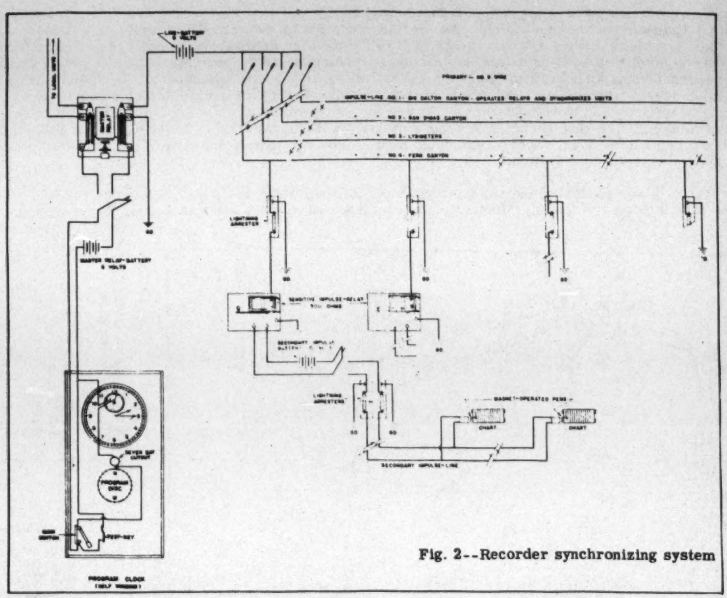


Fig. 2--Recorder synchronizing system

desired. It has already been mentioned that an hourly impulse is used but that provision is made to distinguish noon from midnight. This is done by inserting additional clips in the disc so that during the day a special schedule of impulses is made at $11^h\ 30^m$, $11^h\ 55^m$, noon, $12^h\ 05^m$, and $12^h\ 30^m$, after which the hourly sequence is resumed. At night the schedule consists of contacts at $22^h\ 30^m$, $23^h\ 00^m$, $23^h\ 55^m$, midnight, $01^h\ 00^m$, and $01^h\ 30^m$. These patterns are quite distinctive and are of material help to the tabulator.

The time-impulse contactor is operated by the second-hand and produces an impulse some 3-1/2 seconds in duration, which operates the master-relay (see Fig. 6, center). This is a low-resistance (eight ohms), double-arm relay whose contacts are of the shorting type. One contact-arm controls the long-distance circuits, and the other is for short-range operation within the building.

The circuit--So much for the transmitting end of the system. The signals emitted are distributed to the distant recording-instruments over three single-wire grounded overhead-circuits (Fig. 1) from five to eleven miles in length and to local installations through one-quarter mile of underground cable. The necessary quantity of overhead circuit would be costly to construct if built especially for this purpose. However, in this case the system was conceived at the same time that the telephone-lines were being built throughout the experimental area. The pole cross-arms were designed to carry extra wires, or additional arms were added. Time-impulses could be transmitted over existing telephone-circuits by the use of special equipment, but in this case it was considered best to use separate circuits. In general, standard No. 9 galvanized iron telephone-wire of "extra best best" grade was used. One circuit, however, employed No. 12 Copperweld, which is a copper-covered iron wire having about the same line-resistance, namely, 14.7 ohms per mile, as the No. 9 iron wire.

The relay-centers--Since in a grounded circuit of this kind there is a considerable voltage-drop, it is necessary either to supply a sufficiently high potential to produce enough current to

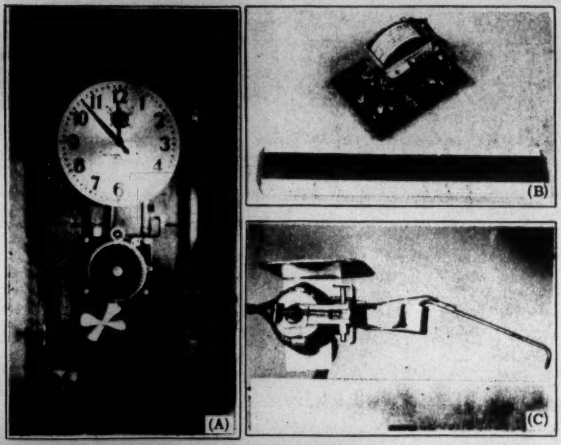
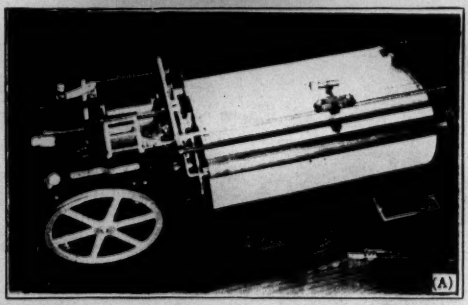


Fig. 3--(A) Master-clock for emission of time-impulses; (B) sensitive relay which receives time-impulses and operates chronograph-pens; (C) chronograph-pen unit as assembled for water-stage recorder



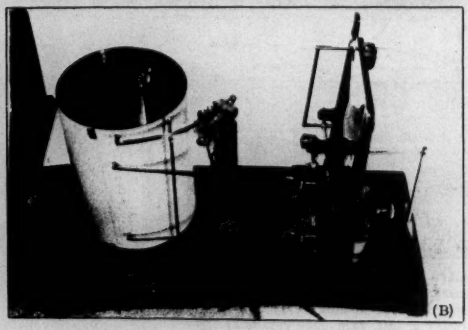


Fig. 4--Use of synchronizer on recording instruments: (A) Water-stage recorder; (B) hygrothermograph

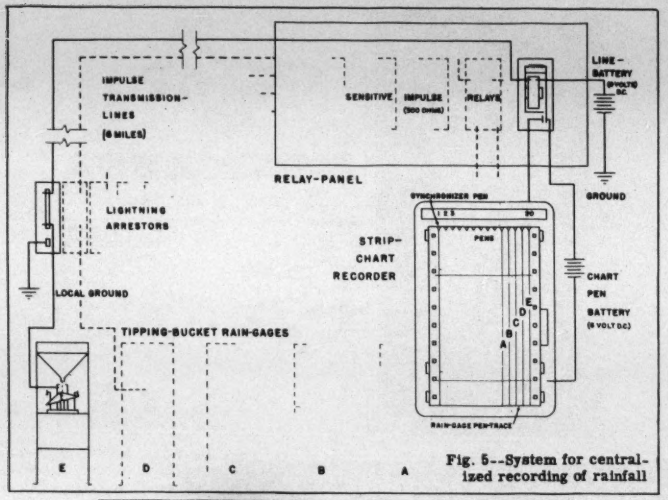


Fig. 5--System for centralized recording of rainfall

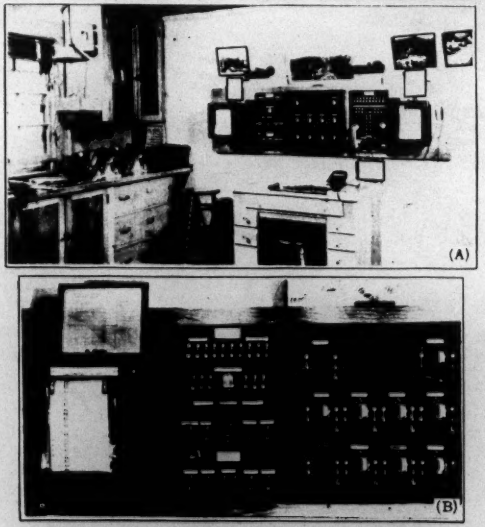


Fig. 6--Control-board for synchronizer and recording instruments in laboratory: (A) General view; (B) detail of control-board showing synchronizer master-relay in lower center, strip-chart recorder at left, rain-gage relays at right

operate a mechanism at the receiving end or to use a low potential that is just sufficient to operate a sensitive relay whose contacts in turn operate the necessary mechanism through a local power-supply. As this latter alternative seemed to offer less complication, it was adopted and relay-centers were established at points where several installations were grouped. These relay-centers (Fig. 1) coincided generally with the shelter-cabins that had been built for the use of observers during storms; and since the telephone-lines were directed to the cabins, the circuits could be distributed with a minimum of construction. The relay used (Fig. 3-B) for the operation of the actual chronograph-pen is of a sensitive type with a coil wound for six-volt direct-current and an internal resistance of 500 ohms. This relay can be operated by a minimum current of ten milliamperes. The operating battery of nine volts, at the transmitting end of the system, is sufficient to overcome easily all line-losses so that six volts at 13 milliamperes are available to operate the relay. Metallic circuits of No. 9 iron wire or No. 14 insulated copper wire convey the secondary impulses to the recorder-pens. These pens were made up on the job from standard parts, the chief of which is the coil, armature, and frame of the magnet-operated pen used in a time or operation strip-chart recorder. This assembly (Fig. 3-C) was attached to a bracket bearing a protective cover, a capillary pen was soldered to the armature, and an inkwell was made from an exploded .38-caliber Special cartridge.

Chronograph-pens--The supporting bracket of the chronograph-pen is attached to the recorder in such a manner that the pen can mark freely on the margin of the chart (Fig. 4). In the case of vertical-drum instruments, a vertical support made from a piece of brass rod or angle is mounted on the base of the instrument, and the pen-assembly is fastened to the top so it bears along the upper margin of the chart (Fig. 4). The assembly can readily be swung out of the way when charts are changed. With multi-pen strip-chart recorders, the left-hand pen is utilized for the chronograph. A water-stage recorder in which the chart-drum is rotated by changes in stage rather than by the clock, is more difficult to synchronize, but it can be done by modifying the carriage so that the stylus and chronograph-pen are combined. The time-impulse will interrupt the record-trace in the form of a jog every hour.

Centralized recorder for tipping-bucket rain-gages--Another phase of the synchronization of rainfall-records is the development of centralized recording for tipping-bucket rain-gages placed at various key locations throughout the experimental area (Fig. 5). These gage-placements involve several conditions: (1) Need for an intensity-record in that particular area; (2) proximity of a telephone-line; and (3) necessity for the gage to be below the mean snow-line, which in this area is about 4,000 feet, since tipping-bucket gages will not record snowfall-intensity. The gages are connected with the laboratory at the Tanbark Flat field-headquarters by grounded circuits similar to those used for the synchronizer-lines (Fig. 1). The recording-procedure follows the same steps as the synchronizer-operation, except that the initial impulses originate in the field where the repeated filling of the tipping-bucket makes an electric contact at the gage for each 0.02 inch of rain. These impulses operate a relay in the laboratory whereby the appropriate pen on the strip-chart recorder is activated (Fig. 6). The instrument control-board is shown in Figure 6 with a detailed view of the relay-panel (right). The strip-chart recorder has 20 magnet-operated pens that work on six-volt direct-current with a current-consumption of 0.20 ampere each. The chart is good for one week's operation at a speed of six inches an hour. The recorder receives its time-impulse from the master-clock through the left-hand pen, which thus makes a convenient reference-line for the entire chart. Five gages record side by side on the same chart, one of them being in the building while the others are from one-half mile to six miles distant. The resulting record gives a clear picture of the rainfall-rate over a considerable area, well-referenced to the stream-flow recorders which note the reaction of the stream-flow to the rain.

Figure 7 is a reproduction of a portion of the strip-chart for October 12, 1942, when a storm passed along the front of the San Gabriel Mountains from the west to east and produced rainfall of rather high intensities at elevations of 1,500 to 2,400 feet, while but 0.06-inch rainfall was recorded in the valley below and similarly low amounts on the mountain peaks. The left-hand portion of the chart gives a record of direction and velocity of wind, with which we are not directly concerned at the moment. The five tipping-bucket gages at the right are designated by the letters A to E, respectively. Each jog along the line represents 0.02 inch of rain. The situation of the gages in the field is similar to their placement on the chart--that is, A is the farthest west and E is the farthest east (see map, Fig. 1). A, C, and E, however, are at elevation about 2,100 feet while B and D are at 2,800 feet. It will be noted that at about $01^h\ 00^m$ a sudden burst of rainfall-intensity affected the low-elevation gages, passing from west to east and reaching each at intervals of four minutes with a shower at the rate of two inches of rain per hour, while at the upper elevations the rain continued at a uniform rate of one-half inch or less per hour. Very shortly after the initial intensity slackened at gage E, a second shower reached A and proceeded eastward in the same manner as the first. This was an unusual storm but not a freak. It is very interesting from a meteorological point of

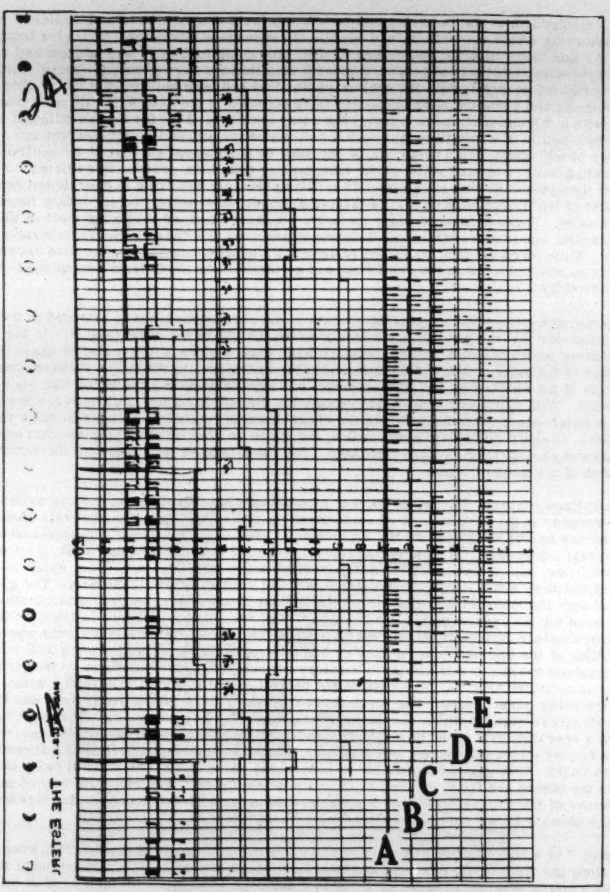


Fig. 7--Reproduction of strip-chart for October 12, 1942, when storm passed along front of San Gabriel Mountains

view, and its interpretation was considerably simplified by the synchronized record.

Thus far, synchronization of weekly or longer records only has been discussed. It is common practice on the San Dimas Experimental Forest to operate weighing-type rain-gages with drive-gears that revolve the chart-drum once in 24 hours. Since the clock has an eight-day movement, during fair weather the recording pen merely makes a horizontal trace as the drum goes around and around. If the synchronizer-circuit were connected all the time, the chart would acquire an overlapping time-pattern by the end of the week. Consequently the circuit is broken during rainless periods but provision is made to throw the synchronizer-line in circuit immediately upon the

start of rain or very soon thereafter. This is readily accomplished automatically through the use of a locking-type relay energized by that paragon among contact-devices, the magnetic mercury switch. This switch consists of a sealed glass tube containing a small pool of mercury in the bottom and an armature, one end of which is a contact-wire held a short distance from the mercury by a light spring. If the armature is approached by a magnet, the wire is pulled into the mercury, and a contact is established. The high merit of the device is that the actuating contact is frictionless and the points are non-corrodible. In this instance a tiny horseshoe permanent magnet is attached to the rain-gage catchment-bucket support, and the glass tube of the switch is suitably mounted so that the magnet is about one-sixteenth inch distant. As the rain fills the bucket, the latter is depressed, and the magnet approaches the armature enough to make a contact. This contact naturally is momentary as the magnet descends but it is sufficient to energize a relay whose points are locked immediately by a spring-catch, thereby throwing the synchronizer-line in circuit.

Lightning-protection--Since the synchronizer-lines are associated with telephone-circuits and are mounted on pole-lines traversing mountainous country, they are subject to the effects of lightning. This, fortunately, is not as prevalent in southern California as in other sections of the country, but the electrical storms that do occur are most virulent in nature. Since the potentials produced by lightning-storms are sufficient to wreck delicate recording-instruments if allowed free access to the circuits, considerable thought was given to protecting the system. A substation protector of the type used on rural telephone-lines was adopted (Fig. 2). It consists of a gap-discharger employing carbon blocks separated by a dielectric, combined with a five-ampere fuse. The former provides a convenient outlet to ground for ordinary electrical concentrations while the fuse gives the added protection needed in case of severe strikes of lightning near the line or of crosses with electric power-circuits. These protectors have been installed at both ends of the primary circuits and frequently at one or both ends of the secondary circuits. If the fuse is blown the line is rendered inoperative, of course, until a replacement has been effected.

This synchronizing system has been in service on the San Dimas Experimental Forest for five years. It provides an excellent time-checking service and gives a permanent record on the chart without interfering with the normal operation of the recorder-clock. The system has been of untold value in the compilation and interpretation of hydrologic data and has saved many hours for constructive work that might otherwise have been spent in attempting to adjust the time-scales on recorder-charts.

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Forest Service, U. S. Department of Agriculture,
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DISCUSSION

L. L. HARROLD (U. S. Soil Conservation Service, Washington, D. C.)--The author has presented a brief description of methods used on the San Dimas Experimental Forest for synchronizing hydrologic instruments, a subject extremely timely. One has only to work with rates of rainfall and runoff for small watersheds but a short time to see the necessity for synchronizing the two records. A few years ago when only storm-totals or monthly and annual rainfall and runoff were used for plot and small-watershed analyses, crude synchronization was all that was required. This synchronization was accomplished by keeping all the rain-gage and water-stage recorder-clocks operating as closely to correct time as possible. At times the clocks were 15 minutes or more in error.

With the development of hydrograph analyses, such as those of A. L. SHARP and H. N. HOLTAN, and others, it was found that an error of one minute or more often materially reduced the accuracy of the results. Sometimes errors of one or two minutes in synchronization of records of rainfall and runoff for watersheds of three acres in area, eliminated the possibility of deriving the amount of surface-detention, initial abstraction, and the shape of the recession-curve of infiltration.

The use of a marginal pen (described by the author) for synchronizing all types of rainfall- and runoff-instruments in which the changes of depth or stage actuate the pen-movement, appears to be simple and effective. At some of the stations for hydrologic research of the Soil Conservation Service this same device has been used. At two of our other stations they have developed and tested a synchronizing device in which a spark burned a hole in the margin of the chart-paper. A spark-coil from a Model-T Ford and dry-cell batteries were used to produce the spark. It was found that one spark was not enough to cause a perceptible burn on the chart but that ten sparks were sufficient. In operating the relay ten times in rapid succession, however, the 1,950-ohm relay was

found to stick in a closed position thereby discharging the battery. To overcome this difficulty, a vibrating induction-coil which will give a number of sparks with one closing of the relay for a few seconds is being tried.

In order to obviate the necessity of installing a special synchronizing-pen on the instrument, the following suggestion came from the station for hydrologic research of the Soil Conservation Service at Coshocton, Ohio: An electrical impulse from headquarters operates a sensitive 1,950-ohm relay at the water-stage recorder-station which releases a vertical rod. One end of this rod is in an air dash-pot and on the other end is fastened a spring-wire pawl. As this rod settles in the dash-pot, the pawl comes in contact with the sponge-rubber tread on the circumference of a disk fastened concentrically to the pen-arm shaft. The disk is rotated as the rod settles to the bottom of the dash-pot and the recorder-pen makes a short mark on the chart. When the potential is removed ten seconds later the relay returns to its non-operating position, lifting the rod up in the dash-pot, disengaging the pawl from the disk, and allowing the pen to return to its normal position. As the air dash-pot takes about six seconds to operate, it eliminates the possibility of false synchronizing marks from flashes of lightning that may close the relay.

Although untried, there is a possibility that this same principle could be used on a weighing-recording rain-gage. The pawl could be made to catch on the side of weighing-platform or on a disk attached concentrically to the pen-arm shaft. For water-stage recorders in which the stage rotates the drum, the pawl could be made to catch on the float-wheel.

As stated by the author, synchronization of rainfall- and runoff-recorders becomes a special problem for some stations during periods of no rainfall and runoff, especially when the chart remains on the drum for several revolutions. The Soil Conservation Service has many such installations. The synchronizer control-device in use at the San Dimas Forest is ingenious in that it throws the synchronizing circuit into operation after a small amount of rain has fallen. A similar contrivance was devised at our East Lansing Station by W. U. GARSTKA. Here under this scheme the synchronizing system is placed in operation similarly to that at San Dimas, after a small amount of rain has accumulated in the weighing-recording rain-gage. The clock of the water-level recorder is held in non-operating position during periods of no runoff even though rain falls, and is not released until runoff begins. This release is automatically operated through rotation of the float-wheel as the float rises. For watersheds where only rainfall and runoff are measured and correlated by individual watersheds, the synchronization-system could be placed in operation automatically at the time the water-stage clock is mechanically released for operation when runoff begins.

In passing it appears desirable to mention a synchronizing gadget which was devised and tested but found to be too expensive to construct and too laborious to install. This gadget operated on the principle of moving all the clock-drums in position so that all charts read the same time. This shifting was accomplished by a two-prong fork plunged vertically against horizontal dowels fixed in the base of the vertical clock-drum, or by electromagnet. The latter method required the use of a magnetic clutch to free the gears before the timing-magnets moved the clock-drums to correct time. These devices were designed to synchronize all the charts so that corrections to the time-graduations on the charts would not be required. It was concluded that it is more desirable to use time-marking synchronizers and apply corrections to chart-graduations than to use devices that moved the clock-drums.

The writer feels that the subject of synchronization of hydrologic records, especially those of small watersheds, is of sufficient importance to warrant considerable attention at all field-stations.

A METHOD OF HYDROLOGIC ANALYSIS IN WATERSHED-MANAGEMENT

P. B. Rowe

This paper presents an outline of a method of hydrologic analysis in watershed-management. The procedure described entails the detailed accounting and evaluation of the effects of present and predicted watershed-conditions on the course of precipitation from its occurrence to its final disposition in the watershed. The approach requires not only determination of character and extent of effects of watershed-conditions on floods, water-conservation, and stream-flow, but also knowledge of physical elements and processes controlling these effects.

Although comprised in part of the adaptation of established methods and in part of new methods, the approach does not forego the use of certain established engineering techniques in handling such

items as stream-flow routings and hydrograph-analyses. Rather it supplements these by permitting a more thorough examination of the influences of individual watershed-factors, particularly those subject to change through land-use or management, on precipitation, soil-water, and runoff-relations within watersheds. Techniques used and sequence of procedures followed in the method are not fixed but may be adapted on the basis of different watershed-conditions and availability of data to best accomplish the purposes of individual analysis.

This method was developed in connection with forest-influences and watershed-research conducted by the California Forest and Range Experiment Station. Modified to fit local watershed-conditions, it has been employed in hydrologic analyses of several flood-control surveys in California. Data and procedures employed in these survey-analyses are used to illustrate techniques and simplify descriptions. Discussion is concerned chiefly with newer techniques and developments, the more commonly used procedures being described in only sufficient detail to indicate their use in the method. A manuscript giving the complete analysis for an actual watershed is being prepared for publication.

Delineation of hydrologic complexes

One of the first and most important operations of the hydrologic analysis was the delineation of individual hydrologic complexes. A hydrologic complex, for purposes of this analysis, is a watershed-division of relatively homogeneous hydrologic characteristics. It is the smallest division employed as a unit in the application of infiltration and similar hydrologic data to evaluate the influences of watershed-conditions on floods and stream-flow. The hydrologic complexes were delineated, in so far as possible, by a process of working from larger units least subject to change through land-use or management to smaller units most subject to change. The order of delineating the hydrologic complexes varied with watersheds, depending upon purpose of the analysis, completeness of data, and relative importance of different watershed-factors. Final segregation of the complexes was influenced also by the findings of infiltration, hydrologic, and similar inventory studies of the survey.

Precipitation-zones--In delineating the hydrologic complexes, the watershed was divided into zones of approximately equal precipitation-characteristics. These zones were based on isohyetal maps, but in order to hold the number of complexes to a minimum, the zones were, in so far as practical, drawn to coincide with the boundaries of soil, vegetation, and land-use types. As soils, vegetation, and use of a watershed are often dependent upon the amount of precipitation, common boundaries were not unusual. Areal extents, expressed as a percentage of the total watershed, and the average amounts of precipitation were computed for each precipitation-zone.

Cover-types--Boundaries and areal extents of vegetation or cover-types within each precipitation-zone were determined next. Delineation of the cover-types was based on the type of vegetation or cover-condition as, for example, oak-woodland, chamise, grass, cultivated or barren.

Soil and geologic groups and water-storage capacities--Each vegetation-type was divided into soil and geologic groups of similar hydrologic behavior. Soil and geologic types were closely related in the mountainous areas of relatively youthful residual soils but were much less closely related in the valley-areas of deep alluvial soils. Differences in infiltration-capacity and water-storage capacity were the principal criteria used in segregating soil and geologic types.

In certain soil-types there often was a considerable range in soil-depths. If the range was relatively small, or if the areas of different depths were fairly evenly distributed throughout a type, the average depth was normally used in the hydrologic computations. If, on the other hand, a soil-type was composed of definable areas of hydrologically significant differences in depths, the type was divided into two or more soil-depth groups. Most critical of the soil-depths in influencing infiltration-runoff relations were areas of very shallow soils, particularly those underlain by impervious or only slightly pervious rock or hard-pan formations restricting the downward drainage and storage of infiltrated water.

Soil-depths and physical characteristics employed in delineating the soil-types were based on sampling and analysis of soil-samples collected as a part of the infiltration and other inventory surveys. Water-storage capacities were computed in inches of depth for ranges between the wilting-points and field water-holding capacities, and between the field water-holding capacities and field water-saturation capacities (maximum water-holding capacities). Standard or commonly used field- and laboratory-methods were employed in the soil-sampling and analysis.

Water-storage capacities of rock-structures, although often ignored in hydrologic analyses,

proved almost as important in the water-relations of some watersheds as water-storage capacities of the soils, particularly in mountainous and hilly areas of shallow soils. Estimates of the temporary or storm water-storage capacity of individual rock-structures were obtained by detailed analyses of the disposition of precipitation in small drainages of representative and homogeneous geologic formations during seasons of heavy rainfall. In these analyses the soil-moisture deficits or total water required to bring the soils to field-capacity at the start of the rainy season were established, and daily and accumulated amounts of precipitation, stream-flow, evaporation-transpiration, and interception throughout the rainy season were determined. The total water retained by the rock-structures at any time during the season was then computed by determining the difference between total accumulated precipitation and accumulated runoff plus accumulated evaporation-transpiration and interception, plus soil-moisture deficits at the start of the season.

The volume of water retained in the rock-structures was computed at periods of not less than three days after the last storm-precipitation in order to allow sufficient time for the soil-moisture to reach field-capacity. Storage-capacities based on these computations thus included deep percolation. Data of precipitation and runoff used in the calculations were based on actual records, and soil-moisture deficits were determined from field soil-moisture sampling. The evaporation-transpiration and interception-data were based on the results of experiments conducted by the California Forest and Range Experiment Station [7,8] and modified to fit local conditions on the basis of soil-moisture sampling and field-tests made during the infiltration-surveys. The methods employed are described later in this report in the section on the adjustment of the infiltration-capacity curves.

The volume of precipitation retained as temporary storage in individual rock-formations of mountainous watersheds in southern California ranged from as little as one-half inch in depth to amounts equivalent to the highest computed annual infiltration in these watersheds (40 to 50 inches). In many rock-formations the capacity to absorb the percolate from overlying soils, and not total water-storage capacity of the rock, was the limiting factor of storm-storage. Computation of temporary water-storage in such rock-structures, therefore, was based on relations of infiltration and water-storage capacity. For example, total water-storage of a rock-formation during a storm was assumed to be equal to the infiltration-capacity of the rock in inches per hour multiplied by infiltration-time in hours less the yield to storm stream-flow. The amount stored in a rock-formation, of course, cannot exceed its total storage-capacity. Average infiltration-capacity of the rock-structures, after soil-moisture contents reached or closely approached field-saturation, was estimated by careful analysis of recorded relations of precipitation and runoff of small sub-drainages during periods of rainfall-excess.

Land-use--Types and degrees of land-use, including burning, are the watershed-variables most subject to control through watershed-management. Determination of areal extent of land-use conditions for each soil-type or depth-group was the final step in the delineation of the hydrologic complexes. Forest- and brush-types were classified according to the physical age of the vegetation, which was judged by the degree of its recovery since the last fire as compared with normal recovery. Range-types were classified according to degree of grazing and frequency of burning as reflected by such factors density of cover, soil-compaction, and erosion. Farmlands were classified on the basis of type of crop grown and cultural practices employed. Changes in the areal extent of present land-use conditions to represent predicted conditions of the watershed, with and without a watershed-management program, formed the bases for hydrologic computations to evaluate effects of watershed-management on floods and stream-flow.

Tabulation of hydrologic-complex data--Use of the information assembled in delineating the hydrologic complexes was greatly facilitated by the complete tabulation of all data in a flow-table. This table showed chronologically each step of the complex segregations, the unit and areal extent of each segregation, and the essential basic physical data of the complex pertinent to the analysis, such as soil-depth and water-storage capacity. The degree of refinement employed in segregating the complexes was consistent with the objective of the analysis and with the reliability of the basic inventory and hydrologic data employed. Influences of many factors not capable of delineation were believed to be adequately compensated for through use of envelope-curves of infiltration-capacity and adjustment of data of infiltration-capacity to actual conditions of storm and watershed, as described in later sections of this paper.

Construction of composite infiltration-capacity curves

Infiltration-capacity data used in constructing composite infiltration-capacity curves of different hydrologic complexes were for the same soil-moisture, vegetation, and land-cover conditions as those to which the data were applied in the hydrologic analysis. Infiltration-capacity measure-

ments having the best and most direct application were those that most nearly represented the infiltration-capacities of the soils under natural field-conditions. Infiltration-capacity measurements of special relations or conditions, or measurements reflecting avoidable effects of instrumentation, such as soil-beating by simulated precipitation in large drops should, when required, be made as separate studies, but should not be included as a part of the infiltration-capacity data used in constructing the composite curves of the complexes.

Segregation of infiltration-capacity curves--The first step in preparing the composite infiltration-capacity curves was the grouping of curves of individual hydrologic complexes. Influences on the infiltration-capacities of such factors as interception-loss, surface-detention, depression-storage, and resistance to wetting were eliminated by extrapolation of the individual curves from the point of runoff-concentration to zero-time of the beginning of the run [6]. Each curve was also extended sufficiently in duration to permit its application to the range of soil-moisture conditions and storm-precipitation patterns employed in the analysis.

The infiltration-capacity curves for even the most homogeneous of the hydrologic complexes were highly variable and represented a wide range of values. The use of a mean infiltration-capacity curve for the individual hydrologic complex, therefore, would have introduced considerable error in computing duration and amounts of surface-runoff, particularly for rainfall of low intensity. For example, infiltration-capacities of approximately 50 per cent of the area of the normal hydrologic complex were less than the average for the complex. Thus, had the rainfall-excess calculations been based on only the mean infiltration-capacity curve of a complex, no surface runoff would be indicated except for rainfall occurring at rates above those of the average infiltration-capacity curve of the complex.

Construction and use of average infiltration-capacity curves--The most reliable estimates of surface-runoff were obtained when rainfall-excess was computed on the basis of the infiltration-capacity and areal extent of individual infiltrometer-tests of the various complexes [6]. Although desirable, this entails a prohibitive amount of computing in many surveys. A modification of this method, employing three or more average infiltration-capacity curves for each complex, was used in California surveys, and resulted in appreciably greater accuracy than methods employing only the single average infiltration-capacity curves of individual complexes.

In constructing the three average infiltration-capacity curves of individual complexes a master

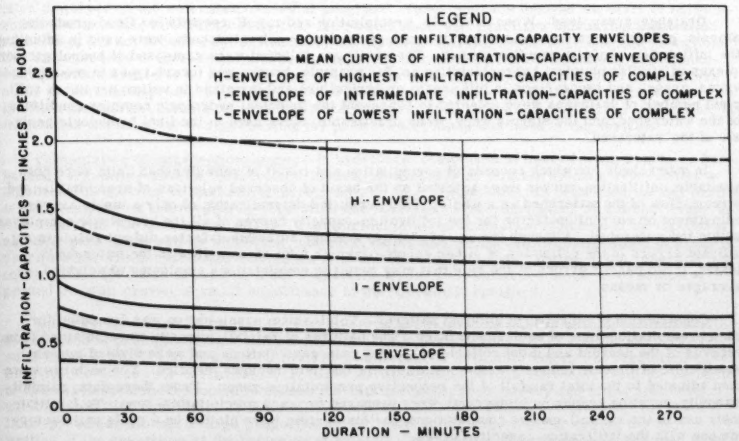

Fig. 1--Average infiltration-capacity curves of high, intermediate, and low infiltration-capacity envelopes of a hydrologic complex

envelope-curve delineated by the highest and the lowest of the individual infiltration-capacity curves of the complex was first drawn. The master envelope-curve was then divided into three envelope-curves: One enclosed the individual infiltration-capacity curves in the upper two-thirds of the master-envelope between the average of the individual infiltration-capacity curves of the complex and the upper envelope-boundary; one enclosed the corresponding infiltration-capacity curves in the lower two-thirds of the master-envelope; and the third enclosed the individual infiltration-capacity curves between the two outer envelope-curves. As shown in Figure 1, average infiltration-capacity curves were next developed for each of the three envelope-curves. The areal extent, or portion of the total complex represented by each average curve, was determined by the number of samples within the envelope on which it was based. The areal extent of each average curve expressed as a percentage of the complex, multiplied by the areal extent of the complex expressed as a percentage of the watershed gave the areal extent of the curve as a percentage of the total area of watershed.

The use of only three average infiltration-capacity curves for each hydrologic complex did not completely eliminate the error resulting from the use of average values in the rainfall-excess computations. By compensating for many of the unsegregated variables influencing infiltration, however, it greatly improved the accuracy of the runoff-calculations. Likewise, there is little likelihood in the limited sampling in most surveys that the full extremes of infiltration-conditions of individual complexes were measured. When the infiltration-sampling was comparatively uniform between complexes and when the infiltration-capacity curves were adjusted to fit actual rainfall-runoff conditions, these limitations were partly offset and appeared to have little or no significant influence on the final results.

Adjustment of infiltration-capacity complex curves to measured relations of storm and discharge

Factors necessitating the adjustment of small-plot infiltration-capacity measurements to measured rainfall-runoff relations of larger areas have been discussed in recent hydrologic literature [1]. They include: (1) Differences between relations of runoff and ground-water of small plots under restricted and artificially applied rainfall and those of large watersheds under natural rainfall; (2) lack of refinement in the measurements of amounts and intensities of natural rainfall and runoff; and (3) inadequacy of existing information and lack of sufficiently refined and tested techniques for isolating and evaluating the influences of precipitation, runoff, infiltration, and time-area relations between plots and larger areas.

Drainage-areas used--When available, precipitation and runoff-records for flood-producing storms, preferably unit-storms of small drainage-basins or subwatersheds, were used in adjusting the infiltration-capacity complex curves. The drainages selected were composed of hydrologic complexes of similar physical characteristics as, for example, brush- and forest-types in mountainous areas, grass- and range-types in hill areas, or agriculture and farmland in valley-areas. A sufficient number of drainages were selected to represent the principal hydrologic complex conditions of the watershed, and the storms were, when practicable, those used in the final hydrologic analysis of the watershed.

In watersheds for which records of precipitation and runoff of subwatershed units were not available, infiltration-curves were adjusted on the basis of observed relations of precipitation and stream-flow of the watershed as a whole. This permitted determination of only a single average adjustment or correction-factor for the infiltration-capacity curves of all the hydrologic complexes within the watershed. Although the use of a single average adjustment-factor did not result in significant errors in the estimates of either runoff-peaks or total stream-flow in the watersheds tested, it did permit errors of the type that may result in computations employing unweighted averages or means.

Construction of storm-precipitation patterns--Total-storm precipitation was computed for each precipitation-zone of each subdrainage. The patterns of rainfall-intensity were obtained from records of the nearest and most reliable recording rain-gage stations and were divided into as small units of time or intensity as the sensitivity of the field-records justified. The patterns were then adjusted to the total rainfall of the respective precipitation-zones. From these data, rainfall-intensity-duration graphs or histograms were prepared for each precipitation-zone. To facilitate their use in the rainfall-excess computations, the histograms were plotted on a scale satisfactory for use with the infiltration-capacity curves.

Analyses of hydrographs--The storm-hydrographs were next divided into their component parts of surface-runoff (precipitation-excess), ground-water flow or runoff, base-flow (depletion

ground-water flow from antecedent rainfall), and channel-storage. A modification of the procedure described by HORTON [4] was employed in the hydrograph-analyses. Ground-water-depletion curves were developed for each drainage from the records of measured stream-flow. An equation of the type $y = (ae^{bx} + ce^{dx})$ was employed to permit the extrapolation of the depletion-curves to the higher values normally occurring under the point of inflection on the recession-side of the hydrograph. The depletion-curves were also employed to separate the base-flow or stream-flow of antecedent precipitation from the storm-flow. The accretion-side of the ground-flow was initially constructed in accordance with the HORTON method [4], but was later checked and adjusted on the basis of computed rates of ground-water yield. After the surface-runoff of a storm had been determined, channel-storage was computed and graphs of surface-runoff inflow were constructed for use in testing the infiltration-capacity curves.

Factors influencing application of infiltration-data--Before the unadjusted infiltration-curves were tested against the results of observed storms, studies were made of various conditions and water-relations of the watershed and subdrainages influencing the application of infiltration-data. These included: (1) Computation of soil and substratum (rock) water-storage capacities as previously described; (2) determination of depression-storage (water stored in soil-depressions); (3) computation of interception-losses for the storms analyzed, and of losses by interception and evaporation of antecedent storm-precipitation; (4) computation of rates of ground-water yields from the different hydrologic complexes; (5) determination of soil-moisture and rock-water storage-space available at the start of storms; and (6) determination of direct rainfall-interception by stream-channels, gullies, and similar areas.

Determinations of depression-storage--Studies of the effects of depression-storage were made in connection with the infiltration-sampling. Depression-storage as determined by the infiltration-tests was deducted from the initial rainfall-excesses of each hydrologic complex. It was recognized that the actual amounts of depression-storage exceeded the amounts determined by infiltration-sampling but, for practical purposes, the differences appear to have been counteracted by runoff from areas in which surface-runoff occurred during periods of rainfall at rates below those of the infiltration-capacity curves of the complexes.

There were considerable increases in total depression-storage and, therefore, total infiltration as the result of remedial measures of certain of the watershed-management programs, owing largely to the higher infiltration-capacities and the more rapid drainage of depressions between periods of rainfall-excess. In agricultural areas, such practices as basin-listing and contouring were often employed in the watershed-remedial program These methods delayed the start of surface-runoff and extended infiltration-time but, unless combined with practices increasing infiltration-capacities, did not necessarily, particularly during large storms, result in flood-peak reductions. The effectiveness of mechanical measures employed to reduce runoff by increasing depression-storage was assumed to be reached when ground-precipitation less accumulated infiltration was equal to the total depression-storage created by the measure employed. For hydrologic complexes in which mechanical measures were combined with practices increasing infiltration-capacities, the infiltration-capacity curve representing the practice employed was used in the analysis.

Computation of interception-losses--In hydrologic complexes of heavy forest, brush, or herbaceous vegetation-covers, interception-losses, particularly of smaller storms, represented a significant proportion of total storm-precipitation. Interception-loss, as here used, is that portion of the precipitation intercepted by vegetation and returned to the atmosphere as a direct evaporation-loss from the surfaces of plants. That portion of the precipitation intercepted by vegetation and delivered to the soil as stem-flow, however, materially influenced the distribution of ground-precipitation within hydrologic complexes of brush- and forest-types. Owing to the generally high infiltration-capacities of soils in these vegetation-types, their influence on the distribution of ground-rainfall proved of small significance in the hydrologic analyses.

Interception-losses of brush- and forest-cover were based on curves developed from studies of relations of precipitation and interception in certain forest-types [7] in California. The results of these studies were modified to fit local differences in density and age of vegetation-cover. Interception-losses for herbaceous vegetation and agricultural crops were estimated on the basis of special field-tests conducted in connection with the infiltration-survey and of the results of various published data [2,3]. Results of interception-studies in California show that for most flood-producing storms a large proportion of the interception-losses occur during the initial wetting of the vegetation at the beginning of rainfall. Interception, therefore, was deducted from initial rainfall of storms and phases of storms.

Calculation of soil-evaporation losses--Soil-evaporation losses, including transpiration, are

important in hydrologic analyses as they affect: (1) Soil-moisture conditions in the application of infiltration-capacity data in rainfall-excess calculations; (2) soil-water storage; and (3) daily and seasonal disposition of precipitation. In hydrologic analyses concerned chiefly with peak-flood flows of individual storms, determinations of soil-evaporation losses, except as they affect soil-moisture conditions at the start of storms, are of relatively little significance and are often unnecessary.

Average soil-moisture conditions of the different hydrologic complexes at the start of the rainy season were determined by soil-moisture sampling, as previously described. Initial soil-moisture content at the start of storms and the evaporation-transpiration losses throughout the season were computed on the bases of (1) results of intensive watercycle-soils investigations made in California [7,8] and (2) results of periodic soil-moisture sampling during the surveys. Calculations of soil-water storage and disposition of precipitation were checked against measured relations of precipitation and runoff of storms used in the analysis.

Determinations of losses by evaporation and transpiration were usually simplified by combining the two and computing the average total losses by 10- to 15-day intervals. In California nearly all the effective rainfall occurs during the winter rainy season. With the close of the rainy season most of the water in the soil available for evaporation, except in occasional areas with high water-tables, is either utilized by vegetation or lost as direct evaporation. Total seasonal losses, therefore, were equal to the loss during the rainy season plus amounts stored in the soils and available for evaporation at the end of the rainy season plus occasional small amounts of interseason infiltration from summer storms. In analyses for which data were not available for direct calculation of losses by evaporation, the evaporation-losses were computed from measured relations of precipitation and stream-flow of the watershed.

Computation of rates of ground-water yield--Although ground-water runoff of individual hydrologic complexes often comprised a major part of total storm and seasonal runoff, it normally constituted only a small portion of runoff during actual periods of maximum or peak-flood flows. This was true particularly of the larger floods. When the soil and substrata of a hydrologic complex became saturated, and the point of runoff-concentration was reached, the rate of runoff from the complex (surface-runoff plus ground-flow), however, approached the rate of precipitation minus the yield to temporary rock-storage and deep seepage. Runoff caused by saturation of the soil and rock-formations of individual complexes often constituted an appreciable part of the flood-flows of southern California streams. The principal purposes of the studies of ground-water yield, particularly as applied to watersheds as a whole, were to provide a more accurate basis for determining rates of ground-water yields and the point or time of saturation of individual complexes than arbitrary analyses of the storm-hydrographs.

Two approaches were used in establishing the rates of ground-water yield to stream-flow. In shallow soils underlain by impervious or nearly impervious rock or hard-pan formations, rates of yield were based upon the degree of saturation of the soils. In deeper soils and soils underlain by the more pervious rock-formations, rates of ground-water yield were based on total retention of water. Although the saturation-basis is the more correct approach, scarcity of reliable basic data and the complexity of time-area relations in hydrologic complexes of deeper soils and pervious rock-formations limit its use in such areas.

To establish correlations between rates of ground-water yield and moisture-content of the soil between field-capacity and saturation in the hydrologic complexes of shallow soils, a series of depletion-curves were constructed for selected subdrainages. The drainages selected for the purpose were (1) composed of relatively homogeneous soil-types of similar hydrologic characteristics, or of soil-types sufficiently different in hydrologic behavior to permit isolating rates of water-yield from the different types and (2) composed of hydrologic complexes representative of those throughout the watershed as a whole. Depletion-curves for hydrologic complexes of the selected drainages were corrected for losses by evaporation. A curve showing average rates of ground-water yield for different soil-moisture contents was then constructed for each complex. To construct this curve, observed rates of yield in inches per hour were plotted over computed soil-moisture contents expressed as percentages of oven-dry weight of the soil, as shown in Figure 2. When depletion-curves used in developing relations of ground-water yield and soil-moisture were representative of the conditions of season and storm of the hydrologic analysis to which they were applied, it was often unnecessary to correct them for losses by evaporation.

In deeper soils and soil-types underlain by pervious rock and substratum formations, the ground-water runoff was, in large part, yielded to streams as flow through the rock and substratum formations. Depletion-curves for these soil-types were often very different, particularly in respect

to the duration of yields, from depletion-curves for soil-types underlain by impervious rock and substratum formations. It is in the soil-types underlain by pervious substrata that the greatest flood-control and water-conservation benefits can be derived from watershed-management.

Relations of rates of ground-water yield to total water-retention (total accumulated infiltration

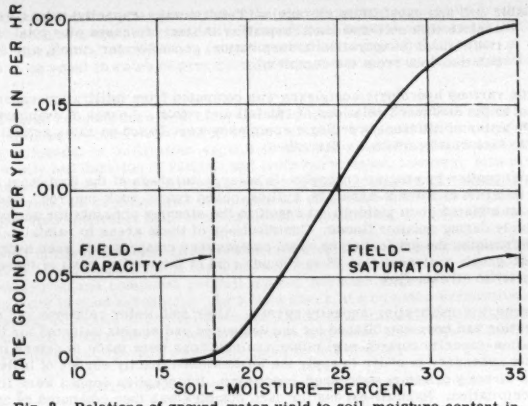

Fig. 2--Relations of ground-water yield to soil-moisture content in a shallow-soil type of a California drainage-basin

of the season minus total accumulated losses by evaporation and ground-water yields of the season) for different hydrologic complexes of pervious substrata were determined in much the same manner as the relations between rates of ground-water yield and soil-moisture contents. Only records of storms occurring under watershed-conditions representative of those to which the data were to be applied were used in establishing these relations. Total infiltration was assumed to be the difference between total ground-precipitation and total surface-runoff. Ground-water components of the hydrographs of the subdrainages were separated from surface-runoff; average ground-water depletion-curves were constructed; and evaporation-losses were calculated by the same procedures outlined in the foregoing discussion. A curve similar to that shown in Figure 2, except that the rates of yield in inches per hour were plotted over total water-retention and not over soil-moisture, was then constructed for each complex.

A simple method often used to advantage was to establish the relation between water retained in a complex or subdrainage and the time-base of the depletion-curve of the complex. The water yield-retention curve was then computed directly from the depletion-curve of the complex. When a subdrainage contained more than one hydrologic complex, rates of yield of individual complexes were separated by a comparison of physical conditions, water-storage capacities, and infiltration-capacities of the different complexes. Breaks or changes in the trend of average depletion-curves of subdrainages also often indicated points at which storage-capacities of various more critical formations became limiting factors, and rates of ground-water yields of these formations became relatively constant.

Total computed rates of yield of hydrologic complexes were checked against total known yields of the watershed as a whole. In this check the weighted totals of the rates of ground-water yield of individual complexes at any given (routed) time should agree with the known yield of the watershed at that time, as indicated by the watershed ground-water curve (accretion or ground-water depletion-curve). Computed rates of ground-water yield were used principally in calculating the accretion ground-water flows of hydrographs. The height of ground-water curves or peaks of ground-water flows of actual hydrographs employed in the analysis were checked by placement and backward extrapolation of the normal depletion-curves.

Calculation of soil and rock-water storage available at the start of storms--Determinations of total and temporary soil-storage capacities and maximum rock-water storage capacities have been discussed. Soil and rock-storage space available at the start of storms was estimated simply by computing the difference between total available water-storage capacity of the soil and rock-formation of each hydrologic complex and total water retained by each complex at the start of the storm, as indicated in the following formula:

> (Available soil and substratum storage) = (Total storage-capacity) minus [(moisture contained in soil-and-rock formation at start of season plus total infiltration) minus (evaporation, transpiration, ground-water runoff, and deep percolation-loss from the complex)]

Infiltration of the various hydrologic complexes was computed from infiltration-capacity curves, roughly adjusted to the measured relations of rainfall and runoff. Losses of evaporation and yields of ground-water of different hydrologic complexes were based on rates established in the analyses of these factors as previously described.

Rainfall-interception by stream-channels--In many watersheds of the Southwest the interception of the precipitation by stream-channels, gullies, paved roads, rock-outcrops, and similar impervious areas so situated as to yield direct runoff to the streams accounts for an appreciable runoff, particularly during smaller floods. Contributions of these areas to rainfall-excesses were evaluated by determining the proportion or areal extents they comprised in each hydrologic complex. In the hydrograph-analyses from 98 to 100 per cent of the total rainfall of these areas was distributed directly to stream-flow.

Trial adjustment of infiltration-capacity curves--After soil-water relations and conditions influencing infiltration had been established for the drainages and storms selected for testing the unadjusted infiltration-capacity curves, preliminary calculations were made to determine approximate adjustments necessary in order to apply the infiltration-capacity curves of individual hydrologic complexes directly to actual watershed-conditions. Interception-losses were first deducted from storm-precipitation. Rainfall-excess for each complex was then computed by applying unadjusted infiltration-capacity curves to histograms of ground-rainfall of individual hydrologic complexes. Approximate calculations were made also for areas of low water-storage capacities to determine amounts of precipitation-excess from soil-and-rock formations of the complexes that reached field-saturation during the storm. Total computed surface-runoff was then compared with known runoff as determined from the initial analysis of the hydrograph, and the difference in the two values was calculated. Trial adjustments of the infiltration-capacity curves were then made, and the runoff was recomputed on the basis of adjusted values. This process was repeated, and infiltration-capacity complex curves were readjusted until the computed rainfall-excess was approximately equal to the known runoff.

Initial adjustment of infiltration-capacity curves was made on a fixed-percentage basis for each test-drainage. To compute precipitation-excess, histograms of storm-precipitation were plotted on tracing paper to the same scales of time and rate as those used in plotting the infiltration-capacity curves. This permitted using the histograms as overlays on infiltration-complex curves and direct reading of rates of precipitation-excess in inches per hour. Adjusting the ordinate axes of the histograms and replotting rates of rainfall equal to the reciprocal of the adjustment-factor obviated the necessity of redrawing the infiltration-capacity curves in adjusting them to computed soil-moisture and other known or assumed storm-conditions. The sum of the rainfall-excess (rainfall-excess rates as read off the histograms multiplied by their duration in hours), plus runoff due to saturation gave the total excess. The computation work in the initial adjustments of the infiltration-capacity curves was greatly lessened by using constant infiltration-capacity values instead of the actual infiltration-capacity curves. When the drainages selected for testing infiltration-capacity curves contained minor areas of hydrologic complexes for which adjustments had been determined, the adjusted curves were used.

Final adjustment of infiltration-capacity curves--After approximate adjustments of infiltration-capacity curves of individual hydrologic complexes of the test-drainages were determined, the final or exact adjustments were made. The same procedures were used in determining exact adjustments as in determining approximate adjustments, except that ground-water and temporary storage-rates of infiltration complexes reaching saturation and runoff-excess due to saturation were more accurately computed. Soil-moisture content and available water-storage space in the various complexes throughout the course of the storm were determined by tabulating cumulative infiltration, ground-water, and, in areas of pervious or partially pervious substratum formations, losses by percolation. The average water-storage space available at any time during the storm was com-

puted by use of the following formula:

(Available ground-water storage at any time during the storm) = [(Available water-storage at start of storm) minus (cumulative infiltration) minus (cumulative ground-water yield plus cumulative deep seepage plus cumulative evaporation)]

When (cumulative infiltration after the start of the storm) minus (cumulative ground-water yield plus cumulative deep seepage plus cumulative evaporation) became equal to available storage at the start of the storm, total runoff-rates from the complex at points of inception of precipitation were assumed to be equal to rates of precipitation minus rates of loss by evaporation and deep percolation.

Results of these computations in drainages tested showed that small changes in intensity and duration of rainfall were closely correlated with rates and volume of surface-runoff. Because of the integrating influences of infiltration-capacities and buffer-effects of soil and rock strata, small changes in intensity and duration of rainfall had little correlation, however, with rates of ground-water yield and percolation. To approximate actual field-conditions more closely, as well as to simplify the analyses, all computations of movements of ground-water were based, therefore, on somewhat longer time-intervals than were employed in computing the rainfall-excesses.

The adjusted infiltration-capacity curves were tested against measured precipitation and surface-runoff of actual storms for several intermediate-sized drainages within the watershed. Although the measured and computed rainfall-excess deviated slightly with different storms, their averages were in good agreement. As a final check, the adjusted infiltration-capacity curves were tested against relations of precipitation and runoff of the watershed as a whole. If the results of this check showed satisfactory agreement between measured and computed surface-runoff, the adjusted infiltration-capacity curves were accepted as satisfactory.

Application of established data to predicted conditions

Storms used--In the hydrologic analysis to determine the effects of watershed-management on floods, records of actual storms were used when available for a range of flood-frequencies sufficient to permit their application to predicted occurrences. The principal advantage of the use of actual storms was that it permitted checking the computed relations of soil-water, runoff, and time-area against measured records of precipitation and runoff under present conditions of the watershed.

When records of actual storms suitable for analysis were not available, storms of desired proportions and frequencies of occurrence were designed by analysis of available precipitation-data of the watershed or region. The methods used were (1) the dimensionless-diagram approach developed by the Hydrologic Section, Flood-Control Surveys of the United States Department of Agriculture, and (2) an approach employing statistical and air-mass analyses of regional storm-conditions, including analyses of measured precipitation- and intensity-data of major storms occurring in the watersheds or region, as devised by the United States Engineer Office, Los Angeles. Because of its simplicity and adaptability and because it is based on recorded precipitation and precipitation-intensity data of the watershed or other comparable locations of the immediate region, the dimensionless-diagram approach was the more commonly used of the two methods. Disadvantages in the use of designed storms were that they did not permit as accurate checks of computed relations of infiltration and runoff or as reliable estimates of the effects of conditions of cover and land-use on stream-flow as did actual storms. These disadvantages of designed storms were in part offset in that they permitted employing unit-storms and assumed similar average watershed-conditions for all storms used in the analysis.

Hydrographs of predicted stream-flow--In constructing flood-hydrographs of actual storms for predicted watershed-conditions, the same procedures were followed in determining relations of precipitation, evaporation, ground-water, and runoff as in the analyses of the subdrainages of the watershed. In analyses of subdrainages, however, precipitation and runoff were the known factors and infiltration-capacities of the hydrologic complexes were the unknown. In hydrologic analyses of storms of the main watershed, precipitation- and infiltration-capacities of the hydrologic complexes were the known factors, and runoff under predicted watershed-conditions was the unknown. In analyses employing designed storms it was of course necessary to compute runoff for both present and predicted watershed-conditions.

Studies of actual records of precipitation and runoff of the watershed were made: (1) To de-

termine average soil-moisture and ground-water storage at the beginning of storms selected for analyses; (2) to develop a ground-water depletion-curve of the watershed; (3) to establish base-flow or stream-flow from precipitation antecedent to storms analyzed; and (4) to determine relations of precipitation, runoff, ground-water yield, temporary storage, and time-area of flood-producing storms, as in analyses for each sample drainage.

Because of greater areas and longer reaches of stream-channels in the watershed as a whole, time-relations of ground-water flows were often appreciably different from those for the smaller subdrainages studied. To determine the relations of water-yield and time for designed storms it was necessary, therefore, to duplicate for the main watershed the studies made of recorded storms in the subdrainages. Determination and prorating of ground-water yields and temporary water-storage of individual hydrologic complexes, on the other hand, were based on results of studies of the subdrainages.

Surface-runoff was distributed to hydrograph form by means of distribution-graphs [5,9]. These were normally computed for a reference-point in the main stream immediately above the

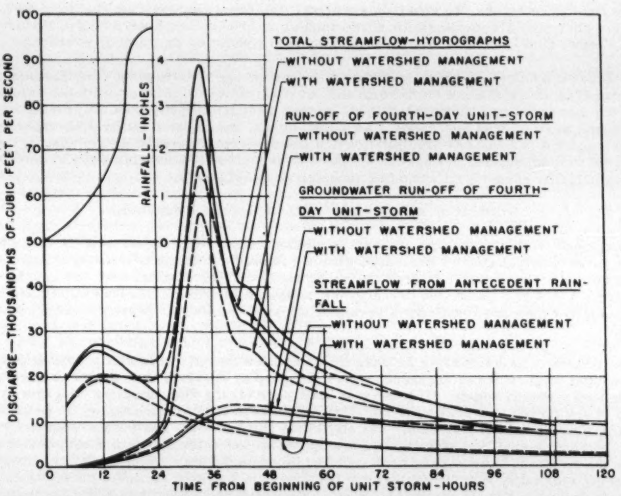

Fig. 3--Hydrographs of 25-year designed storm under predicted watershed-conditions in a typical southern California watershed with and without watershed-management

principal flood-damage areas of the watershed. For watersheds composed of drainages of unequal channel-reaches or irregularly distributed hydrologic complexes, it was often necessary to compute hydrographs for individual drainages, routing the flows through the main river-channel to the reference-point, where they were combined to form the composite storm-hydrograph for the watershed, as shown in Figure 3.

Flood-frequency curves--After peak-discharges were determined for present and predicted watershed-conditions, flood-frequency curves were prepared to show expected differences in flood-peaks under the different watershed-conditions. The flood-frequency curve for present watershed-conditions was based on records of past floods of the watershed or region and was, therefore, representative of relations of precipitation and runoff as influenced by average past watershed-condition. The same frequencies were assigned to peak-discharges under predicted conditions of the watershed as for the respective storms under present watershed-conditions.

Summary

This paper outlines a direct approach to hydrologic analyses for determining the physical effects of watershed-management on floods and stream-flow. Special emphasis is placed on evaluating the influences on the disposition of precipitation of those factors which are subject to change through land-management.

The procedures comprise in part the adaptation of established methods and in part new methods developed in forest-influences research and employed in flood-control surveys in California. Established and commonly used techniques are described in only sufficient detail to indicate their use in the general approach. Essential steps of the procedure include: (1) Delineation of watersheds into complexes of similar hydrologic characteristics; (2) construction of composite infiltration-capacity curves of individual hydrologic complexes; (3) adjustment of infiltration-capacity curves to measured storm and stream-discharges; (4) application of established relations of precipitation, infiltration, soil-water, and runoff to present and expected future watershed-conditions.

Although comparatively simple in application, the method entails careful, detailed accounting of the course of precipitation from its occurrence to its final disposition in the watershed. The approach requires not only determination of the character and extent of the effects of the watershed-conditions on floods, water-conservation, and stream-flow, but also knowledge of the physical elements and processes controlling these effects. The techniques used and sequence of procedures followed can be readily adapted to different watershed-conditions and to the objectives of individual analysis.

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DISCUSSION

J. KITTREDGE (University of California, Berkeley, California)--The development of a logical method by which data of infiltration, soil-water, precipitation, and vegetation can be integrated as a means of estimating the effects of land-use on stream-flow and floods is a valuable contribution. It involves a complete accounting of the disposition of the precipitation that falls on a drainage-basin and the prediction of the disposition of storms of any magnitude that may occur. The method appears to be sound and the author states that good agreement and satisfactory checks against actual data are obtained on small drainage-units where intensive sampling is possible. It is difficult, however, to evaluate the usefulness of the method without examples of the quantitative data for actual drainage-basins. Such evidence will doubtless be forthcoming in a subsequent more detailed publication.

Some of the factors which must be evaluated like transpiration, evaporation, interception, and

deep seepage are notably difficult to determine even by comparison, because of the scarcity and variability of such data. Consequently, figures derived from estimates of these factors must certainly be in the nature of approximations.

If maps of soil and vegetation are available, the complexes can be delimited without great difficulty. However, the soil-surveys rarely extend into the mountains above the cultivated lands so that considerable soil-surveying would become necessary. This could be accomplished along with the sampling for infiltration provided that such sampling is sufficiently intensive.

The whole question of the amount of sampling for factors of infiltration and soil-moisture and the consequent expenditure of time and money may be a serious consideration. The conditions which affect infiltration and soil-moisture are complex and highly variable and it may be expected that determinations of these factors will show wide dispersion even within the unit-complexes. The number of samples necessary to obtain reliable averages may be large. Moreover, if the sampling is to be used not only to obtain averages, but also as a means of determining by proportion the areal extent of different complexes, then the sampling should be both representative and random Obviously the location of an adequate number of random samples in rough and inaccessible country may be a costly procedure. If it would be necessary to adopt this procedure for each of the complexes, the possibility is suggested that the random sampling might be applied to the whole drainage-area as a unit. The resulting infiltration and other data could then be classified and applied according to the frequencies of the different classes as representing areal subdivisions of the drainage-area. This would avoid the necessity of delineating complexes although it would also doubtless require a somewhat larger number of samples.

The curves of infiltration in relation to time are developed by means of envelope-trends through the highest and lowest points. Ordinarily the borders of an array of points are not well defined. It might be more satisfactory to use the procedure worked out in other connections by which a series of curves representing classes are derived from the general average trend for all the data, by spacing the curves above and below this average trend according to convenient percentages or multiples of the standard deviation or coefficient of variation.

A procedure is suggested for adjusting the infiltration-values derived from infiltrometer-determinations for actual watersheds. The magnitude of these adjustments is not indicated although comparisons of infiltration by means of infiltrometer-measurements with those for large watersheds in the literature indicate that the adjustments may be large. If, for example, it should become necessary to reduce the infiltration-values by as much or more than one-half, the question would immediately arise as to whether so large an adjustment-factor would not be variable and require special study for the different parts of a drainage-basin.

In determining available ground-water storage, at any time during a storm, the available storage-space or pore-space at the start of the storm is reduced by the total infiltration and increased by the sum of ground-water runoff plus deep seepage and by evaporation, all cumulated. It would also be possible to express the same relation as the amount of water in storage by reversing the signs of the factors.

For existing conditions, the estimation of stream-flow or floods would be much simpler and perhaps as reliable on the basis of past records and the direct relation between precipitation and stream-flow. This would not provide, however, for the forecasting of runoff after changes in the vegetation or land-use. Actually, the relation of precipitation to runoff for existing conditions has been used as an essential factor in adjusting the infiltration-values.

If the superstructure represented by the proposed method seems a little large for the foundation of meager existing information for most drainage-basins, that difficulty is largely temporary and does not detract from the interest and suggestiveness of the paper.

H. J. FITTINGER (U. S. Forest Service, San Francisco, California)--This paper outlines a workable and practical method of solving the problem of watershed-behavior under varying conditions of cover and land-use. The necessary breakdown of a watershed for study and analysis, while broadly limited to areas of homogeneous precipitation-characteristics, is primarily governed by types of vegetation and land-use. These factors are the only physical features affecting the problem that are subject to change and can be so manipulated as to change characteristics of absorption and water-yield.

Each "complex" as sampled and analyzed represents an area of homogeneous hydrologic characteristics and, while it represents the smallest watershed-division studied, it is also made

as large as permitted by similarity of precipitation-distribution, soil-depth and textures, underlying rock-structure (or sub-strata), and vegetation. It is evident that this breakdown into sub-areas could resolve itself to micro-intensity, reverting to test-plot coverage of an area, but the writer here limits the breakdown into sub-areas to the reliability and coverage possible under the precipitation-data available and employed.

Applying results of infiltrometer-tests by the envelope-curve method should produce sufficient refinement and be well within the accuracy allowed by basic data available.

It would be most desirable in this type of survey to install intensity-gages and to obtain accurate stream-flow records from the sub-areas as a part of the study to adjust the curves more accurately before final application. In these newer "pioneer" studies this information is almost a necessity to modify and verify calculations and to make findings unassailable. There are possibilities of errors between the complexes which may be compensating and which will not appear in a final check against rainfall-runoff relationship for the watershed as a whole.

It is apparent that the author has applied all possible factors affecting the runoff and has followed through in his approach, making use of all available data on each subject, and in some cases adjusting sample (theoretical) values by use of measurements and observations in the field.

While this method and its application have been developed and used primarily to evaluate effects of land-use and cover-improvement (protection) for flood-control surveys, the data resulting from these studies will be of inestimable value when applied to land-use and water-management.

On a completely analyzed watershed it will be possible to estimate directly the price paid in water-use (loss) by vegetative cover and to place in the balance a water-use by vegetation against its value in maintaining a more sustained and usable water-flow. Value of vegetation in erosion-control can then be evaluated separately and a real approach to the problem of dollar values of watershed-lands may result.

R. L. STEVENS (Washington, D. C.)--Mr. Rowe's paper deals more with an explanation of some techniques employed in an analysis of the effects of watershed-management on runoff than it does with presenting a method of analysis. Unfortunately, the author has elected to use terminology not particularly descriptive of parts of his subject and throughout the paper the interchange of ill-defined terms confuse and obscure the main outline of the subject.

The multiple use of such terms as water-storage capacities, storm-water storage-capacities, water-storage capacities of rock, water-holding capacities, rock-storage, ground-water, ground-water yield, soil-water yield, storm-depletion curves, normal depletion-curves, depletion-curves and accretion ground-water flow makes it difficult for a reader, not particularly familiar with the author's reasoning, to readily follow the analysis presented.

The paper is significant in that it shows the author's recognition of the limitations imposed on use and management of watersheds, under certain conditions, for runoff-reduction due to a lack of capacity of a watershed to retain infiltrated precipitation. Such recognition is a healthy sign of progress in hydrologic thinking. Some exception can be taken to the author's treatment of this significant problem.

Simply stated, the author presents the fact that flood-runoff from the watershed-investigation in California is made up of the difference between effective ground-rainfall and surface-runoff plus infiltrated rainfall which it is not possible to accommodate in the soil- or rock-mantle of a watershed. From this it is concluded that certain analyses are required to determine the extent to which each component will contribute to a flood-hydrograph. The problem cannot be said to be general and applicable to all watersheds. In some watersheds there is sufficient storage-capacity in the soil-and-rock mantle to retain all of the precipitation that infiltrates through the surface-film of the soil. When this is the case, flood-runoff is made up of the surface-runoff produced by rainfall at intensities exceeding the rate at which the precipitation can infiltrate the soil, and the base-flow of the streams. In other watersheds the capacity of the soil-and-rock mantle to retain infiltrated water is limited, and at times exhausted during periods of rain, to such an extent that, in addition to the surface-runoff, precipitation that has infiltrated below the surface will be contributed to a flood-hydrograph. In many watersheds the combination of limited retention or storage-capacities and the sequence and pattern of precipitation is such that the flood-hydrographs during the majority of flood-periods are made up of a combination of surface- and subsurface-flow or of subsurface-flow almost entirely.

In the analysis of the Southern California Watershed, referred to by the author, the variability in the capacity of different soil-cover complexes to retain infiltrated precipitation was recognized. Two types of information were available for analysis: (1) Infiltration-capacities of different soil-cover complexes within the watershed obtained by actual measurement through the use of equipment that simulated rainfall and measured surface-runoff; (2) hydrologic records in the form of precipitation-depth pattern and intensity, and runoff-hydrographs for several watersheds.

It is believed that an unwise choice was made between these data with respect to their relative merits. It was assumed that the most reliable information available was the hydrologic data recorded for the watersheds and that by their analysis elements recorded in combination could be separated and used with complete confidence. It was then concluded that all discrepancies between calculated storm-runoff and measured storm-runoff for a given storm for which records were available were due to errors in the infiltration-capacity data which could be used for calculating surface-runoff only. The assumption was made that, in order to calculate satisfactory results, the infiltration-capacity data relative to the several soil-cover complexes and the surface-runoff estimates therefrom would require adjustment.

Several questions can be raised about this assumption and the subsequent method employed in the adjustment of the infiltration-capacity curves. It is believed that the discrepancy between calculated and observed runoff from watersheds is not due so much to errors in infiltration-capacity data, when such data are properly used, as it is due to the methods employed in the development and application of infiltration-capacity data coupled with the inadequacy of observed rainfall-runoff data or methods employed in isolating surface from subsurface-runoff for the storms used to check the results, and the differences between calculated surface-runoff from a unit-area and total runoff from a watershed.

Specific weaknesses in the method reported upon by the author as having been used in the development and use of infiltration-capacity curves and the inapplicability of some of his assumptions concerning the adjustment of infiltration-capacity curves can be pointed out as follows:

(1) The necessity for grouping measured infiltration-data by the use of envelope-curves and the derivation of several average infiltration-capacity curves to be applied to different areas within a given complex indicates that the original complexes were not homogeneous and that the resulting number of average curves for the same complex in effect represented what could be termed sub-complexes. Refinement in determining infiltration-capacity curves can be carried to a point where an infinite number of curves are obtained. It is probably true that there are as many values of infiltration-capacity as there are measurements made on unit-areas of soil and cover capable of measurement. Within a plot the size of an infiltration-measuring device there are numerous differences in infiltration-capacities between square foot or even square inch segments of the plot. The purpose of infiltration-capacity measurement is to obtain the most reliable estimate of infiltration-capacity that, on the average, represents that of an area set out as being different from other areas. Within an area delineated as having significant recognizable physical differences, the average of infiltration-capacity measurements, if the individual measurements are taken at random, should not deviate significantly from the individual values and the average curve should reasonably represent the infiltration-capacity of the complex. Consistent wide variation in the results between individual measurements indicates heterogeneity in the area being sampled and requires the breaking down of the area into its homogeneous sub-areas.

(2) Surface-detention, interception, and resistance to wetting cannot be accounted for by extrapolation of the infiltration-capacity curves to zero-time. It is impossible to conceive of a correction for surface-detention and interception being made in the same manner as a correction for resistance to wetting.

(3) The author makes no mention of having taken into account infiltration-capacities under different degrees of soil-moisture produced by antecedent rainfall. It is assumed that in the analysis reported, the infiltration-capacity curves were applied to the rainfall-histograms without regard to this factor. If this was the case, the resulting values of calculated surface-runoff would be susceptible to considerable error.

(4) The author states that infiltration-capacity complex curves required adjustment in order to account for: (a) The difference between runoff and ground-water relations of small plots under artificial rainfall and large watersheds under natural rainfall; (b) the lack of refinement in measurement of natural rainfall and amounts and intensities of runoff; and (c) the inadequacy of existing information and tested techniques for isolating and evaluating influences of precipitation, infiltration, and time-area relations between plots and larger areas.

In the main none of these factors should actually have any bearing upon the adjustment of infiltration-capacity curves. Infiltration-capacity curves are used solely for the purpose of determining surface-runoff from a unit of area of a given soil with a given cover in a specific condition. If a reliable estimate of surface-runoff can be obtained by the application of infiltration-capacity curves to rainfall-intensity patterns, adjustment to reconcile discrepancies between calculated surface-runoff and the total observed runoff should not be applied against the data used in determining the surface-runoff.

There is considerable confusion concerning the relationship between surface-runoff on unit-areas and total runoff from watersheds. This confusion results from a lack of understanding of the limitations imposed upon the use of the surface-runoff calculated by the application of infiltration-capacities or by any other method in determining total flood-runoff. Many individuals have bemoaned the fact that measured hydrographs of flood-flows produced by natural rainfall cannot be duplicated by the use of infiltration-capacities and attribute the lack of agreement to the use of infiltration-capacities. If judgment and sound techniques are employed in calculating surface-runoff and if it is recognized that surface-runoff, in many instances, is only one of the contributions to the flood-hydrograph, reliable estimates of total runoff can be obtained.

The author has apparently attempted to throw all of the discrepancy between calculated surface-runoff and measured total flood-runoff from a watershed into the surface-runoff calculation. The factors the author catalogues as having an influence on the adjustment of infiltration-capacity curves are in an entirely different sphere than these which influence surface-runoff calculations.

Where the capacity of the soil-mantle to retain the infiltrated precipitation is exhausted before or during the storm, the infiltrated precipitation, in excess of the storage-capacity, is contributed directly to the flood-hydrograph.

When this holds true a procedure for calculating runoff becomes one of determining the surface-runoff and the runoff due to infiltrated precipitation in excess of the storage-capacity of the soil-mantle. As the author points out, the determination of the runoff in excess of the storage-capacity of the soil-mantle requires a knowledge of the storage-capacity of the soil-mantle at the time of the storm.

This storage-capacity at any given time, is a function of soil-moisture. Given a starting point when it is known that storage-capacity is depleted, the capacity at any subsequent time can be determined by calculating soil-moisture depletion by an acceptable application of data relative to rates of evaporation and transpiration to the sequence of interstorm periods. Very good estimates of storage-capacities can be obtained from observed data of rainfall and runoff by determining the storage-capacity of the soil-mantle at the time of a flood-producing rain through an inventory of contributions to soil-moisture by infiltrated rain and the depletion of this moisture through evaporation and transpiration during the interstorm periods. Such a technique does not employ tedious and empirical procedures in attempting to derive from measured runoff the contribution to hydrographs of the several elements that make up the total runoff at a given time. An attempt to determine the component parts of flood-hydrographs results more in the investigator's fatigue and satisfaction of his curiosity than in a fruitful return in the form of pertinent information. Given satisfactory estimes of surface-runoff and the capacity of the watershed to retain infiltrated precipitation, the total runoff can be estimated with reasonable accuracy without a great deal of knowledge about the distribution of subsurface-water.

In employing hydrologic analyses to determine the effects of watershed-management on flood-flow reduction, it should be recognized that the greatest opportunity to reduce flood-runoff through watershed-management is provided by an opportunity to increase the infiltration-capacities of the different soil-cover complexes on a watershed. The degree to which increases in infiltration-capacities are effective in reducing flood-runoff is dependent upon the ability of the watershed to retain the additional infiltrated precipitation. The possibility of increasing the ability of a watershed to retain infiltrated precipitation is limited to the ability of watershed-management programs to either increase evaporation and transpiration, thus making available at the time of flood-producing rainfall a greater portion of the existing storage-capacity, or to increase the storage-capacity of the soil-mantle by increasing its total depth.

It should also be recognized that the ability of a watershed to retain infiltrated rainfall and to increase this retention-capacity varies from complex to complex throughout a watershed and the estimates of the effect of watershed-management cannot be obtained by determining surface-runoff from individual complexes and storage-capacity for a watershed as a whole. A simple

time-saving truth, worthy of being remembered when calculating the effects of watershed-treatment on runoff, is that such effect is a combination of the difference in surface-runoff under the various watershed-conditions plus the increase in evaporation and transpiration and the additional storage provided by the added soil-mantle when part of the total runoff is made up of subsurface-flow. The determination of these differences should not involve serious error.

It is gratifying to note the author's recognition of storage-capacity as a factor in runoff and that storage-capacity places a limitation on the effectiveness of watershed-management programs. It is believed, however, that the assumption that the difference between calculated surface-runoff and runoff measured from a watershed cannot be properly reconciled by making adjustments in data employed in the surface-runoff calculations. It is also believed that in problems of this kind relatively little of value can be obtained from an analysis of hydrographs and tedious studies such as outlined by the author to determine the elements affecting subsurface-runoff. Such labor is unwarranted because the inadequacy of observed data and techniques for identifying different types of flow in a hydrograph and the fact that the extent to which watershed-management programs affect runoff can be measured by the differences between surface-runoff, existing and probable evapotranspiration and storage increases in terms of added depth of mantle.

It is hoped that other investigators will make available clear and concise presentations of their findings with respect to the effects of watershed-management on flood-flows in the hope that our present limited knowledge and accepted use of what appear to be sound new beginnings in the field of hydrology can be developed further.

P. B. ROWE (communicated May 15, 1943)--Mr. Stevens has raised several relevant questions concerning the hydrologic procedure presented and has severely criticized the writer's use of technical terms.

Unfortunately, in his reference to the limited possibilities of watershed-management to increase "the ability of a watershed to retain infiltrated precipitation" and "to have any effect upon anything other than the surface-runoff", Mr. Stevens has introduced an aspect of the subject beyond the scope of the original paper. Since he raised the question, however, it is pertinent to point out that in many mountain watersheds in California deeply weathered and fractured rock-formations beneath the surface-soils provide annually, through gravity-drainage of the rock, temporary storage-space for infiltrated water greatly in excess of the space provided in the overlying soil by annual evaporation and transpiration.

He has also made several misinterpretations and erroneous assumptions concerning the procedure. To avoid further misinterpretation, the writer wishes to explain certain of the more important points in question. (1) The statement in Mr. Stevens' comments, "that flood-runoff is made up of the difference between effective ground-rainfall and surface-runoff plus infiltrated rainfall which it is not possible to accommodate in the soil- or rock-mantle" is probably not intentional. It is the surface-runoff plus infiltrated rainfall not retained by the soil-and-rock mantle, and not the difference between these factors and ground-rainfall, that normally is considered to comprise a large part of flood-runoff. (2) The assumption that soil-moisture was not taken into account in the application of infiltration-capacity data is contrary to several statements in the original paper (see sections on "Construction of composite infiltration-capacity curves" and "Calculation of soil-evaporation losses"). This point has been more frequently indicated in the final manuscript than in the copy reviewed by Mr. Stevens. (3) Surface-runoff was not determined by computing "surface-runoff from individual complexes and storage-capacity for a watershed as a whole," as implied by Mr. Stevens. In fact, determination of water-storage capacities of individual soil-and-rock formations was included as a basic step in delineating the hydrologic complexes (see sections on "Soil and geologic groups and water-storage capacities" and "Computation of rates of ground-water yield").

Mr. Stevens' most important criticism of the procedure concerns the adjustment of infiltration-capacity data obtained from infiltrometer-tests to actual measured rainfall and runoff of watersheds and the application of these data in the analysis. He believes that an unwise choice was made between the infiltration- and the measured rainfall- and runoff-data with respect to their relative merits and suggests that the most satisfactory data available for the analyses were the unadjusted infiltration-capacity measurements of the small plots. This criticism fails to recognize that, while properly executed infiltration-tests afford valid measurements of infiltration-capacities of the soil of individual hydrologic complexes, the tests do not and are not designed to measure the effects of time-area relations on total infiltration. Results of infiltration and small-plot runoff experiments show that these effects are of considerable magnitude. Measurements of precipitation and runoff of actual storms are, on the other hand, integrated factual records of the hydrologic

behavior of the watershed under the conditions existing at the time of the storms. The adjustment of the infiltration-capacity data to such storm-records does not indicate errors in the infiltration-capacity measurements nor does it constitute the grouping of errors that may exist in any one component of the water-cycle. Instead, the adjustment constitutes an integration of the infiltration-capacity data with the actual occurrence of a recorded event.

In hydrologic complexes delineated on the basis of similar conditions of vegetation, soil, geology, and use there are normally variations in infiltration-capacities so numerous and difficult to distinguish and so distributed as to be impracticable of mapping. For use in the analysis the desired homogeneity of infiltration-capacity data was obtained by the grouping of similar infiltration-capacity measurements within hydrologic complexes. As described in the text, the grouping of the infiltration-capacity curves can be avoided by computing rainfall-excess directly from the individual infiltration-curves of the various complexes. Such procedures have proved simpler and more accurate in application than attempts to delineate or map sub-complexes.

Correction for surface-detention, interception, and resistance to wetting was not attempted by the extrapolation of the infiltration-capacity curves to zero-time. These factors were measured independently. Extrapolation of the infiltration-capacity curves was employed simply to eliminate the influences of these factors on the individual infiltration-curves. This is generally accepted as a logical and accurate method of estimating infiltration-capacity during the initial period of the test.

The merits of Mr. Stevens' editorial criticisms concerning terminology are recognized. Only self-explanatory terms or terms commonly used in foresty, soils, and hydrologic writings, however, were employed. The inadequacy and lack of standardization in existing hydrologic terminology have been pointed out by many writers. There can be no question of the desirability of a standard terminology for the developing science of hydrology and perhaps the time has arrived for its formulation.

Dr. Kittredge has presented several constructive criticisms and suggestions concerning the procedure. It is true, as he indicates, that quantitative evaluation of evaporation-losses and deep seepage is often difficult. The evaluation of these factors on the basis of the best available soil-moisture, interception, stream-flow, and allied hydrologic data, however, limits the estimates and permits more certain approximations.

As indicated in the foregoing discussion, the hydrologic complexes were delineated on the bases of similarity of various of the physical factors capable of being employed as units in watershed-management. Owing to the lack of correlation between infiltration-capacities and such factors as interception, evaporation, and water-storage capacities of soil-and-rock formations, random infiltration-sampling, while highly desirable within complexes, would have little application in the general analysis on a watershed-basis. Use of applicable statistical analyses in segregating the infiltration-capacity curves of the hydrologic complexes, as suggested by Dr. Kittredge, would undoubtedly prove of value and tend to further standardize the results.

In practice, the procedure presented has proved somewhat simpler in application and less affected by limitation of data than the outline may indicate. It is believed, however, that in any analysis to determine the effects of land-management on floods and stream-flow, the work of evaluating the influences of the more important individual watershed-factors cannot be avoided if valid results are to be obtained.

GLEANINGS FROM THE FIELD OF HYDROLOGY

C. S. Jarvis

From official observations up to and including the year 1852, and published the following year under the title "Ellet on the Mississippi and Ohio rivers," CHARLES ELLET, Jr., reported the mean annual discharge of the Ohio River at Wheeling, West Virginia, as 835,000,000,000 cubic feet (26,500 cfs), from 24,500 square miles of drainage-area, according to daily records covering all but a few months of the 11-year period, 1838 to 1848. Likewise, for the Mississippi River below Red River Junction, Louisiana, he reported a mean annual discharge of 21,000,000,000,000 cubic feet (665,000 cfs), based on the measurements and intermittent records of those early years, mostly identified with Professor C. G. FORSHEY, Lieutenant ROBERT A. MARR (commanding the Memphis Navy Yard), GEORGE GORDON MEADE (later Major General, United States Army), and himself.

According to the best estimates now at hand, based on all available records to date, tested through various methods of approach or analysis, the 100-year means for those two stations are 39,000 and 630,000 cfs, respectively, derivable from data published in Proceedings of the American Society of Civil Engineers [Proc. Amer. Soc. Civ. Eng., p. 1479, October, 1941]. A considerable number of years with low precipitation within the limits of the 11-year record on the Ohio River may account for some of the difference between the mean given by Ellet and the mean for the century for the Ohio at Wheeling. The 100-year mean for the Ohio River at its mouth, draining 203,900 square miles, similarly derived and published in the same tabulation, was given as 280,000 cfs, thus indicating that a higher yield per square mile occurs in the headwaters-area than in the lower valley, as is customary. The 100-year mean for the Mississippi and Atchafalaya rivers, as published in the tabulation above mentioned, was 668,000 cfs. The irregular interchange of runoff from the Mississippi and Red rivers through the connecting channel of Old River, subject to reversals of flow, introduces some indeterminate factors, so that the remarkably close agreement may be but a coincidence, or it may indicate more reliability than is usually accorded those early gagings.

Apparently the greatest uncertainties relating to discharge of the Mississippi River were encountered in the vicinity of New Orleans in that early period, before the phenomena of salinity-intrusions and underrunning, causing a reversal of flow-direction in deep tidal channels, had been thoroughly investigated. It is not surprising that the combination of tidal and salinity-movements confused the observers somewhat.

It is reassuring to note how those early hydrologists determined the velocity-characteristics of the river cross-sections. Without the modern facilities of current-meters and bridges from which to operate them, they had to rely on the action of floats as observed from the shore or from boats. Ellet noted that a surface-float attached to and supporting a submerged float, usually traveled faster than did single floats, thus disclosing the areas of maximum velocity. Furthermore, the most notable flood-event of record up to 1852, which itself provided a close second, within one foot of the peak at some of the stations, was that of February 11, 1832, at Wheeling, West Virginia, or 1.5 days earlier at Pittsburgh, Pennsylvania, 88 miles upstream, and ten days later at Louisville, Kentucky, 525 miles downstream; while the intermediate station at Cincinnati, Ohio, recorded a period of about 6.5 days for the flood-crest to travel 372 miles.

In a rare document recently consulted at the Library of Congress, it was found that Lieutenant ROBERT A. MARR, acting Commandant of the Memphis Navy Yard, had kept a complete daily record from March 1, 1850, to February 28, 1851, including discharge of the Mississippi River, ranging from 122,000 to 1,070,000 cfs, and averaging 435,000 cfs for the 12-month period. Other items observed were: Rainfall and evaporation, totaling 49.09 and 44.37 inches, respectively; velocity of flow, apparently for the central and the two lateral portions of the cross-section, ranging from 1.11, 1.79, and 1.08 miles per hour for October, to 3.15, 4.18, and 3.62 for March, or, averaging the monthly means, 2.05, 2.97, and 2.22 miles per hour for the period; and sediment carried, 1:2,950 parts by volume.

Ellet's observations covering longer periods at various stations afford indirect confirmation of some of the above items, particularly the burden of sediment and the Mississippi River's discharge-variations from month to month, though inclining with HUMPHREYS and ABBOT toward some 20 per cent higher yield per square mile. His listing of elevations along the various river-channels above Gulf levels shows substantial agreement with those in use today, some differences

Table 1--Comparison basic hydrologic and temperature data with record averages

(P = precipitation in inches, mean of records at selected stations; R = runoff in inches average; dP = observed departure from record average P; dR = computed

Year and no. stations		January			February		
		dT	dP	dR	dT	dP	dR
		°F	in	in	°F	in	in
1817	1	.....	.....	-0.19	.....	.....	-0.14
1818	1	.....	-0.9	+0.56	.....	-0.1	+0.21
1819[a]	1	.....	-0.2	-0.24	.....	+0.3	-0.25
1820	1	-11.8	-2.0	-0.38	+ 4.7	+2.7	-0.24
1821	1	- 5.3	-2.1	+0.13	- 2.1	+1.9	-0.14
1822	1	- 1.0	-2.1	-0.09	+ 3.3	-1.4	-0.04
1823	1	+ 0.5	+1.0	+0.32	-10.6	-1.8	+0.41
1824	0	+ 4.5	(+0.2)	-0.24	- 2.4	(+0.8)	+0.09
1825	0	+ 2.1	(+0.5)	+0.31	+ 9.6	(-1.1)	-0.29
1826	1	+ 0.4	-1.0	-0.39	- 0.4	+0.6	-0.43
1827	1	+ 4.6	-1.8	-0.37	+ 8.3	+3.3	-0.42
1828	1	- 2.3	+0.6	+0.06	+ 0.2	+3.7	+0.26
1829	1	+ 3.3	-0.7	-0.01	- 9.1	-0.7	-0.33
1830	3	+ 1.5	-2.0	+0.36	+ 7.0	-1.5	-0.24
1831	3	- 3.9	-1.3	-0.03	- 2.6	-0.7	-0.24
1832	3	+ 4.5	+0.9	-0.14	-10.1	+4.6	+0.21
1833	3	+ 8.5	-0.6	+0.08	+ 4.3	+0.3	+0.31
1834	3	- 7.1	+1.7	+0.34	+14.6	-1.0	+0.29
1835	4	+10.8	-0.6	-0.21	- 7.3	-1.3	-0.05
1836	6	- 0.3	-0.5	+0.16	+ 0.4	-0.3	-0.14
1837[a]	8	+ 6.8	-1.6	+0.06	+ 8.5	+0.1	-0.25
1838[b]	9	+ 3.6	-0.7	-0.04	-14.0	-1.0	-0.15
1839	10	+ 6.1	+0.1	-0.24	+ 3.7	-0.7	-0.15
1840	13	- 4.8	-1.2	-0.29	+ 5.0	+0.6	-0.29
1841	13	- 2.5	+0.8	+0.41	- 1.9	-1.8	+0.29
1842	13	+ 8.6	-0.2	+0.16	+ 2.6	+1.7	+0.26
1843	15	+ 5.6	-0.6	-0.06	- 9.4	-0.9	-0.07
1844	15	+ 1.8	-0.2	+0.28	+ 6.4	-1.2	+0.21
1845	15	+ 9.5	0.0	-0.01	+ 9.3	-0.7	+0.01
1846	14	+ 7.6	+0.1	-0.24	- 3.4	-0.3	-0.15
1847	14	- 3.9	-0.4	+0.01	+ 1.4	+0.5	+0.21
1848	14	+ 8.3	-0.5	+0.22	+ 5.6	-1.0	+0.08
1849	15	- 2.1	+0.5	+0.22	- 3.6	-0.7	0.00
1850	15	+ 6.1	+2.0	+0.36	+ 2.4	+1.0	+0.37
1851	14	+ 4.3	-1.8	+0.01	+ 3.7	+2.0	+0.19
1852	17	- 3.0	-1.6	-0.19	+ 4.2	+0.3	-0.25
1853	16	+ 3.7	-1.8	+0.38	- 0.7	+0.5	+0.26
1854	17	- 2.9	-0.8	-0.14	+ 4.7	+0.3	-0.12
1855	19	+ 2.5	-0.2	-0.12	- 4.9	-1.4	-0.30
1856	21	-11.0	-0.5	-0.10	- 8.2	-0.3	-0.30
1857	21	-11.8	-1.4	-0.06	+ 7.0	+0.5	-0.11
1858	24	+ 9.4	+0.1	+0.34	- 7.6	-0.3	+0.08
1859	24	+ 2.4	-0.6	+0.26	+ 3.0	+1.3	-0.04
1860	22	+ 2.7	-0.4	+0.06	+ 2.8	+0.4	-0.06
1861	20	+ 0.5	0.0	-0.06	+ 5.0	+0.2	-0.11
1862	19	- 1.7	+1.9	-0.09	- 4.7	+0.3	-0.14
1863	19	+ 6.3	+1.7	+0.02	+ 1.0	+1.1	+0.16
1864	20	- 2.3	-0.9	+0.06	+ 2.7	-1.5	-0.07
1865	21	- 3.6	-0.7	-0.16	+ 2.5	+1.4	+0.02
1866	21	+ 0.7	+0.3	0.00	- 2.2	-0.1	-0.12
1867	26	- 5.6	-0.7	-0.02	+ 4.6	+1.9	+0.22
1868	27	- 5.5	-0.4	-0.17	- 0.2	-1.4	-0.26
1869	27	+ 6.1	-0.1	+0.06	+ 1.0	+0.8	+0.03
1870	27	+ 1.8	+1.3	+0.05	+ 0.8	-0.8	+0.06
1871	27	+ 2.4	+0.1	-0.09	+ 4.5	+0.6	+0.06

and departures from normal for each month and year, Mississippi River Basin

at Vicksburg-Natchez station; T = average temperature; dT = observed departure from departure from record average R; + = excess; - = deficiency)

March			April			May		
dT	dP	dR	dT	dP	dR	dT	dP	dT
°F	in	in	°F	in	in	°F	in	in
.....	.....	-0.01	.....	.....	+0.19	.....	.....	+0.33
.....	+0.2	-0.08	.....	-1.1	+0.05	.....	+2.1	+0.03
.....	+2.1	-0.26	.....	-1.9	-0.26	.....	+0.7	+0.09
- 2.8	-0.6	+0.14	+ 7.2	+0.5	+0.01	+ 2.4	-0.3	-0.07
- 0.2	+0.2	+0.04	- 4.9	+0.8	+0.11	- 1.1	-0.8	-0.02
+ 8.2	-1.3	-0.16	- 1.7	+1.7	-0.43	+ 3.1	-1.5	+0.11
+ 0.7	+2.7	+0.13	+ 3.8	-0.5	+0.09	- 1.3	+1.3	+0.36
- 5.3	(+0.1)	-0.16	- 3.7	(+0.7)	-0.11	- 1.9	(+1.6)	+0.33
+ 7.1	(-1.4)	-0.37	+ 9.7	(-1.3)	-0.21	+ 2.7	(-0.4)	+0.26
+ 0.4	+3.0	+0.17	- 7.8	+1.2	-0.01	+ 8.6	-1.8	-0.11
+ 2.5	-0.7	+0.05	- 0.7	-0.1	-0.01	+ 4.7	-0.8	-0.03
+ 3.0	-1.4	+0.52	- 0.5	+3.1	+0.34	+ 2.1	+2.8	+0.27
+ 0.7	-1.5	-0.47	+ 2.5	+0.6	-0.41	+10.0	-2.8	-0.17
+ 4.8	+2.0	-0.51	+ 6.3	-2.3	+0.09	+ 1.5	-0.6	+0.25
+ 3.1	+0.2	-0.06	- 0.4	-1.3	-0.11	+ 3.4	-0.2	+0.18
+ 8.8	-1.8	+0.34	+ 8.5	-0.5	+0.19	- 2.3	-1.2	+0.13
+ 4.3	-2.1	+0.22	+ 6.3	-2.3	-0.08	+ 2.9	+0.6	-0.24
+ 3.1	-1.3	+0.09	+ 6.2	-1.0	-0.06	+ 3.6	-2.0	-0.35
+ 3.5	-1.6	-0.14	- 1.5	-0.2	-0.16	+ 4.4	+0.7	-0.07
- 9.1	-0.5	+0.13	- 1.8	+0.8	+0.29	+ 6.1	+1.5	+0.38
- 4.7	-0.3	-0.11	- 4.2	-1.5	-0.01	- 4.1	-0.5	+0.03
+ 6.4	-1.4	-0.01	+ 2.4	+0.3	-0.01	- 6.5	+0.6	-0.14
+ 0.9	-0.7	-0.24	+ 7.0	-0.7	-0.28	- 0.2	-0.7	-0.37
+ 3.1	-1.3	-0.04	+ 5.0	+2.8	+0.09	+ 0.3	+0.3	+0.33
+ 2.0	+0.4	+0.04	- 1.2	-0.1	+0.15	- 0.3	-1.1	+0.23
+12.6	-0.8	+0.48	+ 6.9	-0.3	+0.07	- 0.2	-1.0	-0.17
-16.6	-0.2	-0.09	- 0.8	+0.5	-0.16	- 0.2	-0.3	+0.02
+ 2.4	+0.1	+0.19	+10.6	0.0	+0.21	+ 0.7	+1.7	+0.40
+ 1.3	+0.6	+0.27	+ 8.2	-0.6	-0.07	- 2.3	-0.6	-0.15
+ 3.1	-0.6	-0.09	+ 2.9	+1.2	-0.11	+ 2.3	+0.1	-0.02
- 2.7	+0.1	+0.03	+ 3.2	-0.6	+0.11	- 3.5	+0.2	-0.17
+ 0.4	+0.1	+0.11	- 0.9	-1.3	+0.22	+ 2.0	+1.1	+0.29
+ 5.1	+0.2	+0.18	- 1.7	-0.1	+0.34	- 2.2	+1.4	+0.39
- 0.3	+0.6	+0.14	- 6.4	+0.9	+0.09	- 3.6	-0.8	+0.23
+ 4.4	-1.4	+0.42	- 1.7	-1.5	+0.29	+ 2.6	0.0	-0.17
+ 3.9	+0.1	-0.11	- 2.9	+1.2	+0.04	+ 0.4	+0.8	+0.08
- 0.7	-0.9	+0.26	+ 0.7	-0.4	+0.13	- 3.0	+0.1	+0.01
+ 3.5	+1.6	+0.04	+ 1.1	-0.2	+0.04	+ 1.1	+2.2	+0.02
- 4.9	-1.2	-0.41	+ 6.3	-1.7	-0.57	- 0.1	-0.6	-0.36
- 7.9	-1.9	-0.26	+ 3.2	-0.4	-0.31	- 0.8	-1.0	-0.11
- 4.6	-1.6	-0.01	-11.7	-0.9	-0.36	- 5.2	+0.6	-0.25
+ 3.7	-1.0	+0.04	+ 1.6	+0.8	+0.12	- 3.0	+3.0	+0.24
+ 4.8	+1.3	+0.14	- 3.8	+1.2	+0.26	+ 1.9	-0.5	+0.30
+15.7	-2.2	+0.27	+ 2.9	-0.6	-0.35	+ 5.1	-1.4	-0.29
+ 0.1	-0.8	-0.06	+ 1.8	+0.4	-0.03	- 2.7	+0.6	+0.23
- 0.8	+0.8	-0.11	- 2.0	+1.6	+0.05	+ 1.6	-1.3	+0.28
- 0.4	-0.1	+0.19	+ 0.4	-1.1	+0.09	0.0	-1.1	-0.21
- 4.2	-0.8	-0.08	- 5.7	-0.5	-0.11	+ 0.2	-1.4	+0.03
+ 1.4	+1.5	+0.19	- 1.2	+1.7	+0.19	- 0.2	+0.1	-0.09
- 2.3	-0.2	-0.11	+ 3.7	+0.1	-0.11	- 2.8	-1.1	+0.31
-10.7	+0.9	+0.07	- 0.5	-0.5	+0.09	- 6.5	+1.2	+0.25
+ 6.0	+1.4	+0.04	- 5.7	+0.7	+0.01	- 0.5	+0.2	+0.06
- 6.8	-0.2	-0.13	- 2.2	+0.8	-0.01	- 2.4	-0.2	+0.23
- 4.2	+0.1	+0.05	+ 1.7	-1.4	+0.07	+ 4.0	-1.3	-0.09
+ 5.5	+0.6	+0.13	+ 4.5	-1.1	-0.11	+ 0.2	-0.4	-0.25

Table 1--Comparison basic hydrologic and temperature data with record averages and departures

Year and no. stations	January			February		
	dT	dP	dR	dT	dP	dR
	°F	in	in	°F	in	in
1872 27	- 3.8	-1.7	-0.27	- 3.8	-0.8	-0.40
1873 45	- 7.4	+0.3	-0.35	- 2.9	+1.1	-0.13
1874 45	+ 4.1	+0.3	+0.05	+ 1.3	+0.6	+0.06
1875 45	- 8.1	-0.1	-0.08	- 8.8	+0.6	-0.15
1876 45	+11.1	+1.2	+0.26	+ 6.6	0.0	+0.24
1877 45	+ 0.1	0.0	-0.04	+ 7.2	-1.6	-0.03
1926 28	+ 3.5	0.0	-0.26	+ 5.4	-0.3	-0.02
1927 28	+ 0.5	0.0	+0.51	+ 8.4	+0.2	+0.46
1931 28	+ 6.7	-1.7	-0.37	+ 6.9	-0.3	-0.44
1936 28	- 5.7	-0.4	-0.07	-10.4	-0.5	-0.27
1937 28	- 0.4	+4.7	+0.33	- 1.2	-0.6	+1.14
1817-21[c]	- 8.5	-1.3	-0.02	+ 1.3	+1.2	-0.11
1822-26[c]	+ 1.3	-0.3	-0.02	- 0.1	-0.6	-0.05
1827-31[c]	+ 0.6	-1.0	0.00	+ 0.8	+0.8	-0.19
1832-36[c]	+ 3.3	+0.2	+0.05	+ 0.4	+0.5	+0.12
1837-41[c]	+ 1.8	-0.5	-0.02	+ 0.3	-0.6	-0.11
1842-46[c]	+ 6.6	-0.2	+0.03	+ 1.1	-0.3	+0.05
1847-51[c]	+ 2.5	0.0	+0.16	+ 1.9	+0.4	+0.17
1852-56[c]	- 2.1	-1.0	-0.03	- 1.0	-0.1	-0.14
1857-61[c]	+ 0.6	-0.5	+0.11	+ 2.0	+0.4	-0.05
1862-66[c]	- 0.1	+0.5	-0.03	- 0.1	+0.2	-0.03
1867-71	- 0.2	0.0	-0.03	+ 2.1	+0.2	+0.02
1872-76	- 1.0	0.0	-0.08	- 1.5	+0.3	-0.07
60-yr. av. 1817-76	+ 0.4	-0.34	+0.01	+ 0.6	+0.20	-0.03
61-yr. av. 1817-77	+ 0.4	-0.34	+0.01	+ 0.7	+0.17	-0.03
1926-27, 31, 36-37	+ 0.8	+0.52	-0.03	+ 1.8	-0.30	+0.17
1877-81	+ 1.6	.....	.....	+ 2.9	.....	.....
1882-86	- 4.0	.....	.....	+ 0.5	.....	.....
1887-91	+ 2.2	.....	.....	+ 1.5	.....	.....
1892-96	- 1.6	.....	.....	- 1.8	.....	.....
1897-1901	+ 3.9	.....	.....	- 2.8	.....	.....
1902-06	- 0.1	.....	.....	- 5.5	.....	.....
1907-11	+ 3.1	.....	.....	+ 0.3	.....	.....
1912-16	+ 0.6	.....	.....	- 1.7	.....	.....
1917-21	+ 0.7	.....	.....	+ 1.1	.....	.....
1922-26	+ 1.7	.....	.....	+ 1.9	.....	.....
1927-31	+ 0.2	.....	.....	+ 4.5	.....	.....
1932-36	+ 5.0	.....	.....	0.0	.....	.....
1937-38	+ 0.9	.....	.....	+ 3.1	.....	.....
60-yr. av. 1877-1936	+ 1.1	.....	.....	+ 0.1	.....	.....
61-yr. av. 1878-1938	+ 1.1	.....	.....	+ 0.1	.....	.....
120- or 122-yr. av., 1817-1938	+ 0.6	.....	.....	+ 0.25	.....	.....
Record-av. T, P, R	31.1	2.86	0.54	34.8	2.60	0.64
Mean R	.....	.....	0.54	.....	.....	0.64
Discharge 1000 cfs	.....	.....	541	.....	.....	688

and departures from normal for each month and year, Mississippi River Basin--Continued

March			April			May		
dT	dP	dR	dT	dP	dR	dT	dP	dT
°F	in	in	°F	in	in	°F	in	in
- 6.1	-0.6	-0.45	+ 2.1	+0.5	-0.41	- 0.5	+0.2	-0.17
- 2.0	-0.6	+0.09	- 4.9	-0.2	-0.09	- 2.1	+1.5	+0.01
- 0.9	+0.6	+0.09	- 8.8	+2.3	+0.19	+ 1.6	-1.8	+0.26
- 3.9	+1.4	-0.23	- 5.1	-0.5	-0.01	- 2.9	-0.8	-0.07
- 3.6	+1.9	+0.19	+ 1.6	0.0	+0.05	+ 0.2	+0.7	+0.11
- 5.0	+0.7	-0.38	- 1.2	+1.4	-0.25	- 3.4	-0.5	-0.01
- 4.5	-0.3	-0.11	- 5.8	-0.9	-0.24	+ 1.4	-1.1	-0.46
+ 3.8	+1.8	+0.36	+ 0.9	+2.2	+0.45	- 2.5	+1.3	+0.57
- 3.5	-0.6	-0.44	+ 1.2	-0.6	-0.48	- 4.2	-0.7	-0.53
+ 5.1	-0.7	-0.12	- 3.7	-0.8	+0.08	+ 4.2	-1.5	-0.33
- 2.7	-1.2	+0.33	- 1.1	+0.2	-0.44	+ 0.2	-0.5	-0.07
- 1.5	+0.5	-0.03	+ 1.1	-0.4	+0.02	+ 0.6	+0.4	+0.07
+ 2.2	+0.6	-0.08	+ 0.1	+0.4	-0.13	+ 2.2	-0.2	+0.19
+ 2.8	-0.3	-0.09	+ 1.4	0.0	-0.02	+ 4.3	-0.3	+0.10
+ 2.1	-1.5	+0.13	+ 3.5	-0.6	+0.04	+ 2.9	-0.1	-0.03
+ 1.5	-0.7	-0.07	+ 1.8	+0.2	-0.01	- 2.2	-0.3	+0.02
+ 0.6	-0.2	+0.15	+ 5.6	+0.2	-0.01	+ 0.1	0.0	+0.02
+ 1.4	-0.1	+0.18	- 1.5	-0.5	+0.21	- 0.9	+0.4	+0.11
- 1.2	-0.5	-0.10	+ 1.7	-0.3	-0.13	- 0.5	+0.3	-0.07
+ 3.9	-0.9	+0.00	- 1.8	+0.2	-0.07	- 0.8	+0.5	+0.05
- 1.3	+0.2	+0.02	- 1.0	+0.4	+0.02	- 0.2	-1.0	+0.06
- 2.0	+0.6	+0.03	- 0.4	-0.3	+0.01	- 1.0	-0.1	+0.04
- 3.3	+0.5	-0.06	- 3.0	+0.4	-0.05	- 0.7	0.0	+0.03
+ 0.4	-0.15	+0.01	+ 0.6	-0.02	-0.01	+ 0.3	-0.03	+0.05
+ 0.3	-0.14	+0.01	+ 0.6	0.00	-0.01	+ 0.2	-0.04	+0.05
- 0.4	-0.20	0.00	- 1.7	+0.02	-0.12	- 0.2	-0.50	-0.16
+ 0.8	.....	.....	0.0	.....	.....	+ 0.5	.....	.....
- 0.6	.....	.....	+ 1.4	.....	.....	- 2.3	.....	.....
- 1.7	.....	.....	+ 2.7	.....	.....	- 1.9	.....	.....
- 0.1	.....	.....	+ 2.5	.....	.....	- 0.5	.....	.....
+ 0.1	.....	.....	0.0	.....	.....	--0.1	.....	.....
+ 0.8	.....	.....	- 0.6	.....	.....	+ 1.0	.....	.....
+ 6.0	.....	.....	- 2.6	.....	.....	- 2.7	.....	.....
- 3.2	.....	.....	+ 1.4	.....	.....	+ 0.5	.....	.....
+ 5.3	.....	.....	- 1.8	.....	.....	- 1.5	.....	.....
- 1.0	.....	.....	+ 0.8	.....	.....	- 2.1	.....	.....
+ 1.8	.....	.....	+ 1.1	.....	.....	- 2.3	.....	.....
+ 0.9	.....	.....	- 1.0	.....	.....	+ 0.8	.....	.....
+ 3.4	.....	.....	+ 0.3	.....	.....	- 0.5	.....	.....
+ 0.8	.....	.....	+ 0.4	.....	.....	- 0.9	.....	.....
+ 1.0	.....	.....	+ 0.4	.....	.....	- 0.8	.....	.....
+ 0.7	.....	.....	+ 0.25	.....	.....	- 0.3	.....	.....
44.1	3.25	0.82	56.1	3.45	1.00	67.0	3.99	0.97
.....	.....	0.82	.....	.....	1.00	.....	.....	0.97
.....	.....	813	.....	.....	1009	.....	.....	968

Table 1--Comparison basic hydrologic and temperature data with record averages

Year and no. stations	January			February		
	dT	dP	dR	dT	dP	dR
	°F	in	in	°F	in	in
Max. obs.	46.8	7.41	1.07	45.3	7.58	1.76
1000 cfs	.....	.....	1,053	.....	.....	1.944
Year	1880	1937	1927	1930	1832	1937
Min. obs.	18.8	0.79	0.12	20.8	0.73	0.20
1000 cfs	.....	.....	120	.....	.....	216
Year	1918	1837	1928	1938	1877	1931
Max. day	.....	.....	0.050	.....	.....	0.069
1000 cfs	.....	.....	1,560	.....	.....	2,080
Year	.....	.....	1937	.....	.....	1937

		June			July		
1817	1	.....	.....	+0.03	.....	.....	-0.15
1818	1	.....	-1.7	-0.01	.....	+4.3	+0.08
1819[a]	1	.....	-2.0	+0.23	.....	-1.3	+0.19
1820	1	+ 3.1	-0.4	-0.22	- 3.9	+0.2	-0.16
1821	1	+ 6.5	-0.5	+0.03	- 0.5	-0.1	0.00
1822	1	+ 2.4	-0.1	+0.41	+ 2.7	+0.2	+0.29
1823	1	+ 5.3	+3.9	+0.57	+ 3.0	+2.3	+0.57
1824	0	- 1.8	(+1.5)	+0.45	+ 0.2	(+1.2)	+0.45
1825	0	+ 2.9	(0.0)	+0.27	+ 2.7	(0.0)	+0.12
1826	1	+ 4.2	+1.8	-0.13	+ 1.0	+1.1	-0.09
1827	1	+ 4.2	-1.1	-0.08	+ 1.3	-0.6	-0.07
1828	1	+ 4.0	+0.7	+0.33	+ 3.6	+0.5	+0.39
1829	1	+ 5.8	-0.2	-0.29	+ 0.8	-2.5	-0.26
1830	3	+ 2.5	+0.8	+0.33	+ 8.9	-2.3	+0.24
1831	3	+ 2.3	+2.0	-0.01	+ 1.0	+4.5	0.00
1832	3	- 1.8	-1.8	+0.01	+ 0.9	-0.7	-0.06
1833	3	+ 0.4	+0.9	-0.09	+ 2.4	-0.1	+0.19
1834	3	- 0.6	+0.9	-0.37	+ 5.0	+0.4	-0.17
1835	4	+ 0.5	+0.6	+0.23	- 2.2	-1.2	+0.09
1836	6	- 0.4	-1.1	+0.23	- 0.7	+0.7	+0.14
1837[a]	8	- 3.3	+1.5	-0.27	- 1.5	+0.2	-0.31
1838[b]	9	+ 0.7	+0.9	-0.24	+ 7.3	-0.2	-0.21
1839	10	- 4.6	+0.1	-0.32	- 2.4	0.0	-0.31
1840	13	+ 0.9	-0.1	+0.36	- 1.9	-0.4	+0.19
1841	13	+ 2.6	-0.5	+0.05	+ 2.1	-1.3	-0.16
1842	13	- 2.3	+1.1	-0.20	- 3.0	-1.2	-0.25
1843	15	- 1.1	+1.0	+0.38	+ 0.3	-0.5	-0.01
1844	15	+ 0.6	+1.1	+0.58	+ 2.8	+1.4	+0.73
1845	15	- 0.3	+3.6	-0.19	+ 1.0	-0.8	+0.24
1846	14	- 4.2	+1.0	+0.03	+ 2.6	-0.4	-0.13
1847	14	- 3.0	+0.3	-0.17	- 0.2	+1.5	+0.06
1848	14	- 2.5	+0.8	+0.11	- 5.1	+1.3	+0.17
1849	15	+ 0.4	+0.2	+0.23	- 4.4	+3.2	+0.30
1850	15	+ 1.8	+1.3	+0.23	+ 2.0	+0.6	+0.09
1851	14	- 1.6	+0.1	-0.02	- 0.2	-0.2	+0.15
1852	17	- 3.6	0.0	+0.43	- 0.6	+0.2	-0.15
1853	16	+ 3.3	-1.3	-0.22	- 3.4	+1.0	-0.05
1854	17	+ 1.7	-0.4	-0.05	+ 5.8	-1.3	-0.12
1855	19	- 3.3	+0.5	-0.37	+ 0.9	+0.1	-0.29
1856	21	+ 3.5	-1.5	-0.27	+ 4.3	-0.3	-0.22

and departures from normal for each month and year, Mississippi River Basin--Continued

March			April			May		
dT	dP	dR	dT	dP	dR	dT	dP	dT
°F	in	in	°F	in	in	°F	in	in
59.8	5.50	1.46	66.7	5.57	1.61	73.0	7.04	1.60
.....	.....	1,449	.....	.....	1,628	.....	.....	1,620
1860	1830	1903	1844	1927	1922	1896	1858	1922
27.5	1.17	0.30	44.4	1.53	0.43	58.9	1.74	0.34
.....	.....	300	.....	.....	440	.....	.....	335
1843	1860	1830	1857	1837	1855	1907	1834	1895
.....	.....	0.061	.....	.....	0.060	.....	.....	0.082
.....	.....	1,870	.....	.....	1,830	.....	.....	2,495
.....	.....	1937	.....	.....	1922	.....	.....	1927

August			September			October		
.....	.....	-0.09	.....	.....	+0.16	.....	.....	+0.33
.....	+1.4	+0.22	.....	+4.1	+0.13	.....	+0.8	-0.10
.....	+2.4	0.00	.....	-1.9	-0.07	- 3.8	-0.6	-0.10
- 1.4	-2.4	-0.17	+ 1.8	-2.8	-0.16	- 0.6	+1.9	-0.12
+ 5.4	+2.6	+0.07	- 0.5	+3.0	+0.26	+ 0.8	-1.5	+0.13
+ 3.1	-1.8	+0.02	+ 0.4	+1.4	-0.05	- 5.3	+1.5	-0.01
+ 2.3	-0.7	+0.67	- 4.2	-1.0	+0.39	- 0.8	(0.0)	+0.10
+ 0.8	(+1.4)	+0.42	+ 0.8	(+1.8)	+0.21	- 6.0	(+0.8)	+0.01
+ 3.3	(+0.2)	+0.07	+ 2.7	(0.0)	-0.01	- 1.9	(-0.3)	-0.11
+ 0.5	-2.4	-0.19	- 4.9	-1.7	-0.11	+ 1.2	+0.1	-0.13
+ 0.7	-0.7	+0.32	+ 0.8	-2.0	+0.15	+ 1.4	+0.5	-0.02
+ 4.8	-0.9	+0.32	- 1.4	+0.4	+0.23	+ 2.2	-0.4	+0.16
+ 1.6	+1.6	-0.16	- 2.4	+1.0	-0.11	+ 2.6	+0.3	-0.04
+ 3.6	-3.0	+0.07	- 1.5	+0.5	-0.11	+ 6.8	-0.9	-0.16
+ 1.8	+2.4	+0.01	- 5.4	+1.1	+0.02	+ 0.4	+0.5	-0.02
- 2.1	+3.2	-0.03	+ 0.3	-0.7	-0.08	+ 2.8	-0.4	-0.01
+ 1.1	-3.3	+0.06	+ 2.4	+1.9	-0.07	- 6.5	+0.4	-0.01
+ 3.5	-2.2	+0.27	- 3.5	-1.6	+0.19	- 2.1	+0.8	+0.03
- 1.5	+1.1	-0.08	- 5.6	-0.1	-0.08	- 1.2	+1.6	+0.08
- 3.6	+0.7	+0.02	- 3.4	+1.4	-0.05	- 6.0	-1.1	-0.11
- 1.8	-0.3	-0.22	- 1.8	+1.5	-0.12	- 1.4	+0.7	-0.04
+ 2.9	+0.3	-0.15	- 1.9	-2.2	-0.11	- 8.2	-0.4	-0.09
- 3.2	-1.0	-0.17	- 6.1	-0.4	-0.15	+ 4.0	+0.1	-0.16
- 1.5	0.0	-0.03	- 4.8	-0.6	-0.09	- 3.8	-2.5	+0.06
- 0.4	+0.3	-0.19	- 2.4	+0.5	-0.06	- 4.5	+1.2	+0.02
- 4.2	+0.5	-0.20	+ 1.4	-0.5	-0.13	+ 0.2	-1.4	-0.07
- 0.7	-0.8	-0.03	+ 2.8	+2.3	+0.14	- 7.3	+0.2	+0.19
- 0.1	-0.6	+0.77	- 3.5	-1.0	+0.29	- 7.4	-0.1	+0.25
+ 0.1	+0.4	+0.14	+ 0.4	+0.4	-0.08	- 3.5	-0.4	+0.04
+ 1.1	+0.7	-0.13	+ 3.5	+0.1	-0.08	- 2.5	-0.4	-0.10
- 2.8	-0.7	+0.03	- 1.4	-0.5	+0.11	- 1.7	+0.5	+0.13
- 2.5	+0.8	+0.17	- 6.1	-1.4	+0.09	- 3.0	-0.4	+0.03
- 3.7	+1.0	+0.45	- 2.0	-0.6	+0.24	- 5.0	+1.2	+0.18
+ 4.0	+0.5	+0.03	- 0.5	-1.4	-0.03	- 2.2	-0.9	-0.03
- 1.1	+1.1	+0.11	+ 2.4	-1.9	+0.04	- 2.4	-1.0	0.00
- 3.6	-0.3	-0.09	- 2.3	-0.9	+0.03	+ 3.5	+0.5	+0.06
- 0.9	+0.1	-0.05	- 0.2	+0.1	-0.03	- 4.5	-0.9	-0.03
+ 4.8	-1.1	-0.08	+ 6.1	+0.8	+0.07	+ 2.7	+0.9	+0.06
- 2.8	+1.1	-0.10	+ 2.9	+1.6	-0.02	- 4.5	-0.8	-0.01
- 3.3	+0.4	-0.13	- 4.2	-1.0	-0.06	+ 1.0	-0.4	-0.05

Table 1--Comparison basic hydrologic and temperature data with record averages

Year and no. stations		June			July		
		dT	dP	dR	dT	dP	dR
		°F	in	in	°F	in	in
1857	22	- 2.4	-0.4	-0.14	+ 0.7	-0.7	-0.18
1858	24	+ 1.5	+1.6	+0.45	+ 3.4	+1.3	+0.59
1859	24	- 1.7	+0.2	+0.40	+ 1.3	-1.0	+0.09
1860	22	+ 1.2	-0.8	-0.32	+ 3.3	-0.7	-0.25
1861	20	+ 1.8	0.0	-0.12	- 1.3	-0.2	+0.05
1862	19	- 1.4	-1.3	+0.08	+ 0.4	+0.5	+0.05
1863	19	- 4.4	-0.7	-0.21	- 2.8	-1.0	-0.18
1864	20	+ 2.3	-1.8	-0.12	+ 2.1	-1.0	-0.16
1865	21	+ 2.5	+2.0	+0.15	- 3.4	+1.9	+0.36
1866	21	- 0.7	+0.7	+0.18	+ 2.9	+1.2	+0.15
1867	26	+ 3.1	-0.2	+0.25	+ 0.5	+0.9	+0.31
1868	27	- 0.3	-0.3	-0.02	+ 5.2	+0.5	+0.05
1869	27	- 3.2	+1.0	+0.33	- 0.8	+0.3	+0.18
1870	27	+ 1.0	-1.2	-0.14	+ 3.8	+0.2	-0.07
1871	27	+ 3.8	-0.2	-0.10	+ 0.4	-0.7	-0.11
1872	27	+ 1.1	-0.6	-0.09	- 0.2	+2.4	-0.04
1873	45	+ 2.6	+0.4	+0.16	- 1.0	0.0	+0.07
1874	45	+ 3.7	-0.8	-0.11	+ 2.4	-0.1	-0.21
1875	45	- 2.8	+1.2	-0.12	- 1.0	+2.7	+0.09
1876	45	- 1.7	+0.3	+0.20	+ 0.6	+1.3	+0.17
1877	45	- 0.6	+1.9	+0.17	- 0.9	-0.1	+0.09
1926	28	- 2.4	-1.1	-0.46	+ 2.2	+0.1	-0.33
1927	28	- 3.8	+0.2	+0.44	- 1.2	-0.1	+0.27
1931	28	+ 4.6	-1.3	-0.45	+ 3.4	-0.2	-0.40
1936	28	+ 2.2	-2.3	-0.51	+ 8.6	-1.2	-0.41
1937	28	+ 0.4	+0.2	-0.19	+ 1.0	-0.9	-0.18
1817-21[C]		+ 4.8	-1.1	+0.01	- 2.2	+0.8	-0.01
1822-26[C]		+ 2.6	+1.4	+0.31	+ 1.9	+1.0	+0.27
1827-31[C]		+ 3.8	+0.4	+0.07	+ 3.1	-0.1	+0.06
1832-36[C]		- 0.4	-0.1	0.00	+ 1.1	-0.2	+0.04
1837-41[C]		- 0.7	+0.4	-0.08	+ 0.7	-0.3	-0.16
1842-46[C]		- 1.5	+1.6	+0.12	+ 0.7	-0.3	+0.12
1847-51[C]		- 1.0	+0.5	+0.08	- 1.6	+1.3	+0.15
1852-56[C]		+ 0.3	-0.5	-0.10	+ 1.4	-0.1	-0.17
1857-61[C]		+ 0.1	+0.1	+0.05	+ 1.5	-0.3	+0.06
1862-66[C]		- 0.3	-0.2	+0.02	- 0.2	+0.3	+0.04
1867-71		+ 0.9	-0.2	+0.06	+ 1.8	+0.2	+0.07
1872-76		+ 0.6	+0.2	+0.01	+ 0.2	+1.3	+0.02
60-yr. av. 1817-76		+ 0.8	+0.21	+0.05	+ 0.7	+0.30	+0.04
61-yr. av. 1817-77		+ 0.8	+0.24	+0.05	+ 0.7	+0.30	+0.04
1926-27, 31, 36-37		+ 0.2	-0.86	-0.23	+ 2.8	-0.46	-0.21
1877-81		- 0.8	.....	.....	+ 1.3	.....	.....
1882-86		- 0.8	.....	.....	0.0	.....	.....
1887-91		+ 0.3	.....	.....	+ 0.4	.....	.....
1892-96		+ 1.3	.....	.....	- 0.4	.....	.....
1897-1901		+ 2.1	.....	.....	+ 2.0	.....	.....
1902-06		- 1.9	.....	.....	+ 1.0	.....	.....
1907-11		- 0.8	.....	.....	- 0.9	.....	.....
1912-16		- 0.3	.....	.....	+ 1.9	.....	.....
1917-21		+ 1.3	.....	.....	+ 1.4	.....	.....
1922-26		+ 0.6	.....	.....	+ 0.1	.....	.....

and departures from normal for each month and year, Mississippi River Basin--Continued

August			September			October		
dT	dP	dR	dT	dP	dR	dT	dP	dT
°F	in	in	°F	in	in	°F	in	in
- 1.0	+1.1	-0.05	+ 0.8	-1.2	-0.08	- 4.1	+0.1	-0.05
+ 1.2	-0.1	+0.44	+ 0.8	-0.8	+0.15	- 0.2	+1.2	+0.02
- 0.7	+0.4	-0.04	- 3.4	-0.2	-0.01	- 4.4	-1.4	-0.02
+ 0.8	-0.7	-0.11	- 2.8	-0.3	-0.09	+ 0.1	+0.1	-0.05
+ 0.9	+0.2	+0.20	- 1.6	+1.2	+0.09	+ 1.8	+0.8	+0.08
+ 0.9	-0.1	+0.13	- 0.1	-0.1	+0.09	- 2.4	-0.4	+0.09
- 1.7	0.0	-0.04	- 3.0	-1.4	-0.03	-11.7	+0.9	+0.07
- 0.5	+0.4	-0.03	+ 0.6	+0.8	-0.01	- 7.1	-0.1	-0.04
- 1.6	+1.5	+0.43	+ 5.0	+1.6	+0.33	- 1.5	-0.6	+0.12
- 3.0	+0.5	+0.20	- 7.2	+3.7	+0.32	- 1.1	0.0	+0.45
+ 1.9	-1.3	+0.13	+ 1.3	-1.7	-0.01	- 0.7	-0.9	-0.02
- 2.8	+0.6	+0.13	- 7.3	+1.8	+0.21	- 3.5	0.0	+0.09
+ 1.9	0.0	+0.20	- 3.4	+0.1	+0.11	-11.3	-0.8	-0.01
- 1.4	+1.3	+0.06	+ 0.7	-0.6	-0.02	- 0.5	+0.5	-0.02
+ 1.0	+0.7	+0.03	- 3.7	-1.5	-0.02	+ 0.4	+0.4	-0.11
+ 1.8	-0.2	+0.05	- 0.7	-0.4	-0.07	- 2.4	-0.7	-0.11
+ 0.8	-0.5	+0.11	- 3.9	-0.6	-0.05	- 6.7	+0.6	-0.04
+ 0.6	-0.2	-0.15	- 0.5	+0.8	-0.07	- 0.6	-1.2	-0.04
- 4.9	+0.6	+0.45	- 3.5	+0.5	+0.34	- 4.3	-0.5	+0.13
+ 0.9	+0.8	+0.12	- 3.3	+0.7	+0.15	- 3.0	-0.3	+0.17
- 1.6	-0.7	-0.04	- 0.7	-0.1	-0.04	+ 1.8	+1.8	+0.01
+ 1.9	+1.0	-0.20	+ 0.4	+2.5	+0.24	- 0.4	+1.5	+0.53
- 5.3	-0.1	+0.08	+ 4.8	-0.2	+0.06	+ 4.0	+0.8	+0.21
- 0.3	+0.5	-0.23	+ 6.4	+0.6	-0.12	+ 4.1	+0.1	-0.10
+ 8.1	-0.8	-0.30	+ 3.7	+1.7	-0.18	0.0	+0.2	0.00
+ 4.8	-0.6	-0.18	- 0.2	-1.2	-0.09	- 1.8	+1.4	-0.09
+ 2.0	+1.0	+0.01	+ 0.6	+0.6	+0.06	- 1.2	+0.1	+0.02
+ 2.0	-0.7	+0.20	- 1.0	+0.1	+0.09	- 2.6	+0.4	-0.03
+ 2.5	-0.1	+0.11	- 2.0	+0.2	+0.04	+ 2.7	0.0	-0.02
- 0.5	-0.1	+0.05	- 2.0	+0.2	-0.02	- 2.6	+0.3	0.00
- 0.8	-0.1	-0.15	- 3.4	-0.2	-0.11	- 2.8	-0.1	-0.04
- 0.8	0.0	+0.11	+ 0.9	+0.3	+0.03	- 4.1	-0.4	+0.06
- 1.2	+0.5	+0.16	- 1.5	-1.2	-0.09	- 2.9	-0.1	+0.06
- 1.2	0.0	-0.09	+ 0.5	+0.1	0.00	- 0.4	-0.1	+0.01
+ 0.2	+0.2	+0.09	- 1.2	-0.3	+0.01	- 1.4	+0.2	0.00
- 1.2	+0.5	+0.14	- 0.9	+0.9	+0.14	- 4.8	0.0	+0.14
+ 0.1	+0.3	+0.11	- 2.5	-0.4	+0.05	- 3.1	-0.2	-0.01
- 0.2	+0.1	+0.14	- 2.4	-0.2	+0.06	- 3.4	-0.4	+0.02
+ 0.1	+0.14	+0.07	- 1.2	+0.01	+0.04	- 2.2	-0.02	+0.02
+ 0.1	+0.13	+0.07	- 1.2	+0.01	+0.04	- 2.2	+0.01	+0.02
+ 1.8	0.0	-0.17	+ 3.0	-0.68	0.0	+ 1.2	+0.80	+0.11
+ 1.3	.....	.....	- 0.8	.....	.....	+ 1.2	.....	.....
- 1.3	.....	.....	+ 0.3	.....	.....	+ 1.3	.....	.....
- 1.8	.....	.....	- 2.0	.....	.....	- 3.0	.....	.....
+ 0.5	.....	.....	+ 0.7	.....	.....	- 1.0	.....	.....
+ 2.5	.....	.....	+ 3.0	.....	.....	+ 4.1	.....	.....
- 0.8	.....	.....	- 0.3	.....	.....	- 0.1	.....	.....
- 0.3	.....	.....	+ 0.5	.....	.....	- 1.2	.....	.....
- 0.1	.....	.....	- 0.3	.....	.....	+ 0.9	.....	.....
+ 0.1	.....	.....	+ 0.1	.....	.....	+ 0.8	.....	.....
+ 1.1	.....	.....	+ 0.7	.....	.....	- 0.9	.....	.....

Table 1. Comparison basic hydrologic and temperature data with record averages

Year and no. stations	June			July		
	dT	dP	dR	dT	dP	dR
	°F	in	in	°F	in	in
1927-31	- 1.4	.....	.....	+ 1.8	.....	.....
1932-36	+ 3.1	.....	.....	+ 5.1	.....	.....
1937-38	- 0.2	.....	.....	+ 1.9	.....	.....
60-yr. av. 1877-1936	+ 0.2	.....	.....	+ 1.1	.....	.....
61-yr. av. 1878-1938	+ 0.2	.....	.....	+ 1.2	.....	.....
120- or 122-yr. av., 1817-1938	+ 0.5	.....	.....	+ 0.8	.....	.....
Record-av. T, P, R	75.0	4.14	0.77	78.8	3.99	0.60
Mean R	.....	.....	0.77	.....	.....	0.60
Discharge 1000 cfs	.....	.....	773	.....	.....	611
Max. obs.	82.6	7.86	1.49	87.4	8.67	1.35
1000 cfs	.....	.....	1,505	.....	.....	1,340
Year	1934	1845	1929	1901 1936	1831	1844
Min. obs.	68.6	2.23	0.21	73.7	1.90	0.20
1000 cfs	.....	.....	216	.....	.....	198
Year	1928	1832	1934	1848	1830	1936
Max. day	.....	.....	0.057	.....	.....	0.049
1000 cfs	.....	.....	1,740	.....	.....	1,500
Year	.....	.....	1929	.....	.....	1844

		November			December		
1817	1	.....	+1.5	+0.43	.....	-2.4	+0.53
1818	1	.....	-0.8	-0.15	.....	+0.6	-0.22
1819[a]	1	+ 1.1	-2.2	-0.17	+ 2.0	-1.0	-0.26
1820	1	- 1.2	-0.3	-0.06	- 7.2	+0.4	-0.03
1821	1	- 1.2	-0.3	-0.06	- 7.4	-2.1	-0.11
1822	1	- 1.3	+5.7	+0.20	-14.7	-1.0	+0.37
1823	1	- 0.1	(0.0)	-0.14	- 4.4	(0.0)	-0.26
1824	0	- 1.9	(-0.2)	-0.08	+ 4.2	(+1.0)	-0.08
1825	0	+ 2.0	(-0.6)	-0.15	- 3.6	(-0.8)	-0.27
1826	1	+ 3.4	+0.8	-0.17	+ 1.2	-0.7	-0.26
1827	1	+ 0.1	-1.9	-0.07	- 5.0	+5.1	+0.07
1828	1	+ 3.3	+0.5	+0.04	+ 6.9	-2.2	+0.12
1829	1	- 4.7	+1.1	+0.18	+ 7.1	+1.1	+0.38
1830	3	+10.9	+0.9	-0.19	- 2.4	-0.7	-0.13
1831	3	- 0.7	-1.9	-0.06	-14.7	-1.3	-0.24
1832	3	+ 1.6	-0.2	+0.20	+ 7.8	+1.5	+0.29
1833	3	+ 5.2	-0.1	+0.15	+13.4	-0.2	+0.28
1834	3	+ 8.1	+0.4	-0.12	+ 3.8	-1.1	-0.19
1835	4	- 7.5	+2.6	+0.43	- 0.7	-0.9	+0.17
1836	6	+ 2.5	-1.0	-0.11	+ 1.0	-1.1	+0.04
1837[a]	8	+ 5.9	0.0	-0.01	- 0.2	+0.7	0.00
1838[b]	9	-10.7	+0.1	-0.05	- 7.5	-1.5	-0.10
1839	10	- 6.9	-0.2	-0.18	- 4.5	-0.6	-0.24
1840	13	- 2.7	-0.5	+0.14	+ 1.1	-1.5	+0.20
1841	13	+ 0.7	+0.4	+0.12	+ 2.3	+0.7	+0.14
1842	13	- 7.6	0.0	0.00	+ 0.2	-0.7	-0.02
1843	15	- 2.2	+1.3	+0.30	+ 3.1	+0.2	+0.44
1844	15	- 0.8	0.0	+0.20	+ 1.7	-1.7	+0.15
1845	15	- 2.7	-0.9	+0.03	- 7.5	-1.1	-0.17
1846	14	+ 1.0	-0.2	-0.08	+ 4.8	+1.4	+0.19

and departures from normal for each month and year, Mississippi River Basin--Continued

August			September			October		
dT	dP	dR	dT	dP	dR	dT	dP	dT
°F	in	in	°F	in	in	°F	in	in
- 0.7	.....	.....	+ 1.7	.....	.....	+ 1.9	.....	.....
+ 2.5	.....	.....	+ 1.3	.....	.....	+ 0.3	.....	.....
+ 4.5	.....	.....	+ 1.6	.....	.....	+ 2.4	.....	.....
+ 0.3	.....	.....	+ 0.4	.....	.....	+ 0.4	.....	.....
+ 0.5	.....	.....	+ 0.5	.....	.....	+ 0.4	.....	.....
+ 0.3	.....	.....	- 0.3	.....	.....	- 0.8	.....	.....
77.5	3.67	0.43	70.5	3.31	0.31	58.8	2.70	0.27
.....	.....	0.43	.....	.....	0.31	.....	.....	0.27
.....	.....	430	.....	.....	310	.....	.....	267
85.6	7.06	1.21	77.4	7.17	0.77	66.3	5.33	0.80
.....	.....	1,200	.....	.....	779	.....	.....	798
1936	1832	1844	1897	1866	1915	1897	1840	1926
			1933					
70.4	0.52	0.13	63.2	1.04	0.14	47.1	1.01	0.11
.....	.....	125	.....	.....	145	.....	.....	110
1915	1833	1926	1868	1838	1925	1865	1830	1895
.....	.....	0.042	.....	.....	0.031	.....	.....	0.030
.....	.....	1,300	.....	.....	950	.....	.....	900
.....	.....	1844	.....	.....	1915	.....	.....	1926

Annual summaries					
.....	.....	(52.00)	+ 9.9	8.48	+1.42
.....	.....	50.92	+ 8.8	7.77	+0.71
.....	.....	36.30	- 5.8	5.93	-1.13
43.4	-0.8	39.11	- 3.0	5.61	-1.45
43.3	-0.9	43.32	+ 1.2	7.51	+0.45
44.1	-0.1	43.38	+ 1.3	7.57	+0.51
43.8	-0.4	49.34	+ 7.2	10.28	+3.22
43.2	-1.0	(53.00)	+10.9	8.34	+1.28
47.5	+3.3	(37.00)	- 5.1	6.68	-0.38
44.9	+0.7	41.60	- 0.5	5.19	-1.87
46.1	+1.9	41.46	- 0.7	6.57	-0.49
46.4	+2.2	49.50	+ 7.4	10.08	+3.02
45.7	+1.5	39.52	- 2.6	5.45	-1.61
48.4	+4.2	30.78	- 9.1	7.06	0.00
42.8	-1.4	45.50	+ 4.1	6.51	-0.55
45.8	+1.6	44.56	+ 3.1	8.11	+1.05
48.0	+3.8	37.12	- 4.3	7.86	+0.80
47.1	+2.9	35.63	- 5.8	7.01	-0.05
43.4	-0.8	41.82	+ 0.7	7.27	+0.21
43.0	-1.2	42.87	- 0.5	8.01	+0.95
44.1	-0.1	36.88	+ 0.7	5.81	-1.25
54.0	-2.2	31.33	- 5.2	5.76	-1.30
55.6	-0.6	33.82	- 4.8	4.28	-2.78
55.8	-0.4	41.70	- 0.3	7.68	+0.62
55.9	-0.3	41.60	- 0.4	8.04	+0.98
57.4	+1.2	39.30	- 2.7	6.99	-0.07
54.0	-2.2	44.53	+ 2.1	8.10	+1.04
57.4	+1.2	41.92	- 0.5	11.28	+4.22
57.3	+1.1	42.20	- 0.2	7.11	+0.05
57.7	+1.5	44.29	+ 2.6	6.14	-0.92

Table 1. Comparison basic hydrologic and temperature data with record averages

Year and no. stations		November			December		
		dT	dP	dR	dT	dP	dR
		°F	in	in	°F	in	in
1847	14	- 0.3	+1.2	+0.22	- 0.1	+1.3	+0.35
1848	14	- 6.7	+0.6	+0.10	- 1.9	+2.1	+0.20
1849	15	+ 6.4	+0.5	+0.18	- 5.3	+0.2	+0.30
1850	15	+ 2.4	+0.3	+0.05	- 3.1	+1.4	+0.08
1851	14	- 4.6	+1.4	-0.02	- 3.4	+0.1	-0.10
1852	17	- 6.3	+1.5	+0.06	+ 0.7	+1.0	+0.28
1853	16	+ 4.0	-0.2	-0.04	- 0.6	-1.2	-0.06
1854	17	- 1.7	-1.3	-0.04	+ 2.1	-1.3	-0.07
1855	19	+ 1.5	+1.8	+0.04	- 2.3	+0.5	+0.04
1856	21	- 4.8	+1.2	+0.10	- 5.3	+1.1	+0.16
1857	22	- 6.3	+1.3	+0.05	+ 5.6	+0.6	+0.14
1858	24	- 7.8	+0.2	+0.17	+ 3.4	+2.1	+0.22
1859	24	+ 2.0	+0.1	-0.02	- 9.9	+0.7	-0.02
1860	22	- 4.5	+0.9	-0.07	- 4.4	-0.1	-0.07
1861	20	+ 0.8	+0.2	+0.01	+ 4.9	-1.3	-0.05
1862	19	- 3.5	-0.4	+0.05	+ 6.5	+0.7	+0.10
1863	19	- 2.5	-0.2	+0.07	+ 0.5	+0.8	+0.12
1864	20	- 1.3	+1.3	+0.05	- 4.8	+0.5	-0.07
1865	21	+ 1.7	-1.8	0.00	- 4.5	+0.8	-0.02
1866	21	+ 0.2	+0.3	+0.18	- 1.4	+0.2	+0.02
1867	26	+ 2.8	0.0	-0.06	+ 0.7	-0.1	-0.05
1868	27	- 1.9	+0.2	+0.05	- 7.1	0.0	+0.07
1869	27	- 6.1	+0.6	-0.02	- 2.8	+0.3	+0.06
1870	27	+ 1.1	-1.1	0.00	- 4.5	-0.6	-0.06
1871	27	- 6.7	+0.1	-0.15	- 5.8	-0.7	-0.25
1872	27	- 9.3	-1.3	-0.13	-11.6	-0.2	-0.25
1873	45	- 3.9	-0.2	-0.02	+ 1.3	+0.9	+0.15
1874	45	- 1.6	+0.7	-0.09	+ 3.2	-0.4	-0.13
1875	45	- 4.1	+0.3	0.00	+ 8.6	+0.8	+0.10
1876	45	- 3.9	-0.5	0.00	-10.2	-1.1	-0.15
1877	45	- 2.8	+1.2	+0.10	+13.4	+0.2	+0.12
1926	28	- 4.9	-0.1	+0.33	- 1.5	+0.4	+0.30
1927	28	+ 2.6	+1.0	+0.07	- 2.5	+0.5	+0.26
1931	28	+ 9.4	+1.3	-0.14	+10.3	+1.1	+0.16
1936	28	- 2.0	-0.5	+0.06	+ 4.5	+0.3	-0.14
1937	28	- 3.3	-0.9	-0.02	- 2.9	-0.1	-0.17
1817-21[c]		- 0.4	-0.4	0.00	- 4.2	-0.9	-0.02
1822-26[c]		+ 0.4	+0.8	-0.07	- 3.5	-0.3	-0.10
1827-31[c]		+ 1.8	-0.3	-0.02	- 1.6	+0.4	+0.04
1832-36[c]		+ 2.0	+0.3	+0.11	+ 5.1	-0.4	+0.12
1837-41[c]		- 2.7	0.0	0.00	- 1.8	-0.4	0.00
1842-46[c]		- 2.5	0.0	+0.09	+ 0.5	-0.4	+0.12
1847-51[c]		- 0.6	+0.8	+0.11	- 2.8	+1.0	+0.17
1852-56[c]		- 1.5	+0.6	+0.02	- 1.1	0.0	+0.07
1857-61[c]		- 3.2	+0.5	+0.03	0.0	+0.4	+0.04
1862-66[c]		- 1.1	-0.2	+0.07	- 0.7	+0.6	+0.03
1867-71		- 2.2	0.0	-0.04	- 3.9	-0.2	-0.05
1872-76		- 4.6	-0.2	-0.05	- 1.7	0.0	-0.06
60-yr. av. 1817-76		- 1.2	+0.16	+0.02	- 1.3	-0.02	+0.03
61-yr. av. 1817-77		- 1.2	+0.18	+0.02	- 1.1	-0.02	+0.03

and departures from normal for each month and year, Mississippi River Basin--Continued

Annual summaries					
dT	dP	dR	dT	dP	dR
°F	in	in	°F	in	in
54.9	-1.3	45.29	+ 3.6	7.98	+0.92
55.1	-1.1	43.79	+ 2.1	8.83	+1.77
54.7	-1.5	48.51	+ 6.8	10.04	+2.98
56.4	+0.2	47.08	+ 5.4	8.65	+1.59
56.4	+0.2	38.54	- 3.0	7.95	-0.89
55.4	-0.8	44.30	+ 2.7	7.17	+0.11
56.0	-0.2	36.94	- 4.8	7.64	+0.58
58.6	+2.4	41.00	- 0.6	6.66	-0.40
55.4	-0.8	41.43	+ 0.4	4.57	-2.49
53.4	-2.8	35.91	- 4.7	5.49	-1.57
53.4	-2.8	39.25	- 1.7	5.95	-1.11
56.7	+0.5	49.15	+ 8.1	9.90	+2.84
55.5	-0.7	42.56	+ 1.5	8.34	+1.28
58.1	+1.9	34.01	- 6.2	5.73	-1.33
57.2	+1.0	39.76	+ 1.2	7.27	+0.21
55.6	-0.6	40.00	+ 2.1	7.61	+0.55
54.6	-1.6	36.90	- 1.1	7.12	+0.06
52.7	-1.5	32.62	- 5.9	6.50	-0.56
55.9	-0.3	47.64	+ 9.1	8.56	+1.50
55.1	-1.1	43.85	+ 5.3	8.50	+1.44
55.4	-0.8	37.58	- 0.3	8.22	+1.16
54.2	-2.0	40.87	+ 3.0	7.29	+0.23
53.7	-2.5	40.42	+ 2.6	8.07	+1.01
56.5	+0.3	34.57	- 3.3	6.95	-0.11
56.7	+0.5	35.67	- 2.2	6.10	-0.96
53.4	-2.8	35.08	- 2.8	4.69	-2.37
53.7	-2.5	38.86	+ 2.6	6.95	-0.11
56.5	+0.3	37.64	+ 1.3	6.92	-0.14
52.8	-3.4	42.42	+ 6.1	7.49	+0.43
55.7	-0.5	41.20	+ 4.9	8.57	+1.51
56.7	+0.5	40.25	+ 3.9	6.76	-0.30
55.8	-0.4	39.57	+ 1.7	6.36	-0.70
57.0	+0.8	45.40	+ 7.6	10.78	+3.72
59.9	+3.7	35.95	- 1.9	3.51	-3.55
57.4	+1.2	31.43	- 6.4	4.85	-2.21
55.6	-0.6	38.21	+ 0.4	7.43	+0.37
.....	-0.85	.....	+ 2.2	.....	0.00
.....	+0.5	.....	+ 2.8	.....	+0.55
.....	+1.7	.....	- 0.2	.....	+0.07
.....	+1.3	.....	- 1.4	.....	+0.59
.....	-0.7	.....	- 2.0	.....	-0.75
.....	+0.6	.....	+ 0.3	.....	+0.86
.....	-0.7	.....	+ 3.0	.....	+1.63
.....	-0.4	.....	- 1.4	.....	-0.75
.....	0.0	.....	+ 0.6	.....	+0.38
.....	-1.0	.....	+ 1.9	.....	+0.60
.....	-0.9	.....	0.0	.....	+0.27
.....	-1.8	.....	+ 2.4	.....	-0.14
.....	-0.18	.....	+ 0.68	.....	+0.28
.....	-0.17	.....	+ 0.74	.....	+0.28

Table 1. Comparison basic hydrologic and temperature data with record averages

Year and no. stations	November			December		
	dT	dP	dR	dT	dP	dR
	°F	in	in	°F	in	in
1926-27, 31, 36-37	+ 0.4	+0.16	+0.06	+ 1.6	+0.44	+0.08
1877-81	- 2.4	.....	.....	+ 1.1	.....	.....
1882-86	+ 2.1	.....	.....	+ 0.3	.....	.....
1887-91	- 1.1	.....	.....	+ 5.1	.....	.....
1892-96	- 1.9	.....	.....	+ 2.3	.....	.....
1897-1901	+ 1.2	.....	.....	- 1.6	.....	.....
1902-06	+ 1.3	.....	.....	- 0.8	.....	.....
1907-11	+ 0.3	.....	.....	- 0.1	.....	.....
1912-16	+ 4.6	.....	.....	+ 0.6	.....	.....
1917-21	+ 0.5	.....	.....	+ 0.2	.....	.....
1922-26	+ 0.2	.....	.....	+ 0.6	.....	.....
1927-31	+ 2.2	.....	.....	+ 3.0	.....	.....
1932-36	- 0.6	.....	.....	+ 0.6	.....	.....
1937-38	- 0.3	.....	.....	- 0.7	.....	.....
60-yr. av. 1877-1936	+ 0.6	.....	.....	+ 0.9	.....	.....
61-yr. av. 1878-1938	+ 0.6	.....	.....	+ 0.7	.....	.....
120- or 122-yr. av., 1817-1938	- 0.3	.....	.....	- 0.3	.....	.....
Record-av. T, P, R	45.4	2.75	0.29	34.9	2.82	0.41
Mean R	.....	.....	0.29	.....	.....	0.41
Discharge 1000 cfs	.....	.....	295	.....	.....	403
Max. obs.	54.8	5.57	0.76	49.8	5.05	0.75
1000 cfs	.....	.....	771	.....	.....	736
Year	1931	1835	1919	1889	1858	1906
Min. obs.	33.0	1.05	0.09	23.3	0.80	0.13
1000 cfs	.....	.....	90	.....	.....	126
Year	1880	1831	1895	1872	1865	1917
Max. day	.....	.....	0.026	.....	.....	0.030
1000 cfs	.....	.....	800	.....	.....	900
Year	.....	.....	1919	.....	.....	1906

[a] Temperature observed at Minneapolis, Minnesota, 1819 to 1837. [b] Temperature observed at St. Louis, Missouri, 1838 to 1938. [c] Average yearly departure by 5-year

being a few feet and others less than a foot, which could have resulted from change of gage-location. His knowledge that approximately one-fifth of the precipitation within the Mississippi River Basin appears as runoff to the Gulf, prompted his sharp challenge of a statement in one of Lieutenant Marr's reports, to the effect that "only 1/12,000 part reaches the Gulf ....," and led to the remark that more than ten times that amount is discharged in one day. Perhaps that comment of Ellet provides the clue for solving the problem, for his statement seems to apply to daily discharge during high-water, while Lieutenant Marr's is correct if applied to daily discharge during low-water.

Calculations in support of the foregoing conclusions are as follows:

Mean daily discharge at the Gulf, according to Ellet, was 665,000 cfs, or (1/5)(1/365) = (1/1825) of the annual rainfall.

and departures from normal for each month and year, Mississippi River Basin--Concluded

Annual summaries					
dT	dP	dR	dT	dP	dR
°F	in	in	°F	in	in
.....	+0.94	.....	+0.28	.....	-0.37
.....	+0.6	.....	+2.51	.....	-0.69
.....	-0.3	.....	+3.09	.....	+0.60
.....	+0.06	.....	-0.11	.....	-0.21
.....	0.0	.....	-2.55	.....	-1.20
.....	+1.2	.....	-0.93	.....	-0.62
.....	-0.7	.....	+0.01	.....	-0.12
.....	+0.1	.....	-0.55	.....	+0.17
.....	+0.3	.....	-0.42	.....	+0.21
.....	+0.6	.....	-0.44	.....	-0.20
.....	+0.3	.....	-1.33	.....	-0.55
.....	+1.1	.....	-0.64	.....	+0.36
.....	+1.5	.....	-2.10	.....	-1.01
.....	+1.4	.....	+0.13	.....	0.00
.....	+0.4	.....	-0.29	.....	-0.27
.....	+0.5[d]	.....	-0.35[d]	.....	-0.27[d]
.....	+0.16	.....	+0.20	.....	0.00
56.2	.....	39.55	.....	7.06	.....
.....	.....	.....	.....	7.06	.....
.....	.....	.....	.....	593	.....
60.1	.....	49.15	.....	10.75	.....
.....	.....	.....	.....	905	.....
1921	.....	1858	.....	1927	.....
52.8	.....	27.16	.....	3.42	.....
.....	.....	.....	.....	289	.....
1875	.....	1930	.....	1895	.....
.....	.....	.....	.....	0.082	.....
.....	.....	.....	.....	2,495	.....
.....	.....	.....	.....	May 4, 1927	.....

periods (algebraic sums of departures divided by number of record-years).
[d] Comparing means of 61-year segments of record.

The mean discharge during the high-water months usually attained or exceeded 1,000,000 cfs, or 1.52 times the mean.

1.52 (1/1825) = (1/1200), or ten times the original (1/12000) quoted by Ellet from Lieutenant Marr's report, which corresponds to the low-water discharge of about 100,000 cfs and to gage-readings of nearly 0.0 and 5.0 feet at Vicksburg and Natchez, Mississippi, respectively.

Unfortunately, events and conditions interrupted the methodical observations and evaluations of river-discharge and some of the related data for several years or even decades thereafter. When the stream gage-readings were at length resumed, the transformations into discharge-units seemed to lag or to be entirely neglected, until after the turn of the century--the general revival dating from around the year 1930. Associated with this revival of interest and activity were the establishment and development of hydraulic laboratories, together with the expansion of stream-gaging and observations of weather, but the fundamental work had required many years of patient planning and coordinated effort among the responsible Federal and State agencies.

Fortunately the rainfall, temperature, and other climatological data, including daily river-stages and daily forecasts, had become entrenched as essential parts of the United States Weather Bureau records, and these have provided means for strengthening, clarifying, analyzing, and finally evaluating or estimating the stream-discharge during many years of fragmentary, intermittent, or otherwise deficient records. Gradually, after many relatively fruitless quests, a concept has been evolved and subjected to far-reaching tests, whereby the excess or deficiency in monthly or annual precipitation and temperature as compared with the long-period means, may be translated into corresponding excess or deficiency of runoff for like periods. No claim is made as to its being a new concept, for it seems to be a familiar one, even as the unit-hydrograph proved to be, once it was impressed into practical use on widely scattered fronts and found to be fairly reliable as well as logical.

Table 1 represents the application of this method toward the derivation or the testing of the discharge of the Mississippi River at the Vicksburg and Natchez stations by months during 1817 to 1877; likewise for other selected years. For years 1878 to 1938, the results were derived on a yearly basis, then summarized by five-year periods. For the years 1824 and 1825, the method was put into reverse, so to speak, for the purpose of determining the probable monthly rainfall at Marietta, Ohio, during the only break in that notable record of precipitation. Fortunately, the complete hydrographs of Mississippi River discharge at Natchez, Mississippi, were available for those two years.

As should be expected, where several sources of information and various approaches are to be reconciled, there are numerous instances of departures of rainfall and runoff from normal with opposite signs. The border-line cases (wherever the departures from normal are very small) are not significant, inasmuch as the inherent errors or other uncertainties may far overshadow those slight differences developed in the basic data. Where the departures from normal are great, and still have opposite signs, they are well worth investigation. Usually, very logical basis will be forthcoming to explain the unusual situation. For example, the mean of the annual precipitation-depths at 15 stations for the year 1844 proved to be 0.5 inch below normal, yet the discharge of the Mississippi River was found to be 4.22 inches above the long-period mean of 7.06 inches. Explanation is afforded by the excessive rainfall over such portions of Kansas and Missouri for which rainfall-records were kept at that time. The three months of May, June, and July each had nearly double or treble the normal depths, which resulted in providing most of the excess runoff for that season.

Other reversals of sign between departures of rainfall and runoff may occasionally be traced to great departures in prevailing temperatures. For example: February, 1834, averaged 14°.6 F above normal in the Upper Mississippi Valley; the precipitation was deficient by 1.0 inch, or some 30 per cent, while the runoff was in excess by 0.29 inch, or nearly 45 per cent of the long-period mean, undoubtedly due to the premature thaw, as 15 to 20 days might reasonably account for the 706 miles of high-water travel from Cairo to Natchez.

In spite of the progressive increase in the number of rainfall-records available for inclusion, altering not only the annual but also the monthly means and the distribution-pattern throughout the year, the characteristic relationships of excess and deficiency seem to hold fairly well, except for the fact that the Great Plains and Rocky Mountain regions seemed to have too great representation in proportion to runoff-yield and the departures from normal rainfall sometimes appear in runoff of following months.

Illustrating the progressive changes that occur with the increasing number of stations of record, Table 2 of mean monthly and yearly rainfall is presented, beginning with Marietta, Ohio, and then adding all eligible stations in chronological order.

While the monthly runoff-depths over the drainage-area ranged from about 0.1 to 0.3 of the corresponding monthly precipitation, the yearly runoff-depth ranged from about 0.17 to 0.20 of the rainfall-depths for the listed stations, which increased from a single one in 1817 to 50 in 1870.

Even though the monthly temperatures varied considerably at the two stations listed in Table 2, the observed departures from normal were fairly consistent in general. The inclusion of additional stations as they became available, such as Dubuque, Iowa, beginning with the calendar year 1851, also Peoria, Illinois, beginning in 1856, produced such trivial changes in monthly departures as to justify their omission.

Table 2--Comparison of monthly and yearly means for increasing station-groups

Number of stations	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Precipitation, depths in inches													
1	3.41	3.05	3.52	3.40	3.83	4.18	4.58	3.94	3.02	2.86	2.94	3.39	42.13
5	3.76	3.36	3.94	3.74	3.92	4.01	4.28	3.85	3.05	2.80	3.22	3.91	43.85
10	2.93	2.67	3.25	3.44	3.93	4.23	4.30	3.97	3.38	2.71	2.77	3.07	40.63
20	3.28	2.95	3.61	3.81	4.17	4.28	4.17	3.76	3.38	2.85	3.04	3.29	42.59
30	3.24	2.91	3.60	3.74	4.12	4.25	4.13	3.74	3.40	2.79	2.98	3.21	42.06
40	3.02	2.77	3.44	3.63	4.08	4.25	4.09	3.73	3.41	2.71	2.82	3.00	40.94
50	2.75	2.52	3.19	3.43	3.95	4.09	3.87	3.51	3.23	2.64	2.61	2.74	38.50
70	2.53	2.32	2.97	3.25	3.76	3.92	3.71	3.37	3.03	2.46	2.38	2.50	36.12
Runoff, depths in inches at Vicksburg (drainage-area, 1,144,500 sq mi)													
1	0.54	0.64	0.82	1.00	0.97	0.77	0.60	0.43	0.31	0.27	0.29	0.41	7.06
Mean temperatures at Minneapolis and St. Louis in °F													
1[a]	12.7	16.6	29.2	45.5	58.2	67.8	72.8	69.7	60.2	47.9	31.9	18.0	44.2
1[b]	31.1	34.8	44.1	56.1	67.0	75.0	78.8	77.5	70.5	58.8	45.4	34.9	56.2

[a]Minneapolis. [b]St. Louis.

In spite of changing the basis of reckoning temperature-departures from normal, necessitated by the fact that the record at St. Louis, the most nearly representative in the entire valley, began some 19 years later than that at St. Paul, Minnesota, incorporated in the record for Minneapolis, the average departure from normal throughout the first half of the 122-year record is given as - 0.°2 F; the second half of this period, the average departure was + 0.°5 F, thus providing an acceptable closure. If the same record had been used throughout the 122 years, the average annual departures of the two 61-year periods should have been numerically equal, but of opposite signs. Likewise for the widely changing station-group means of monthly and yearly precipitation, accounting for mean annual departures of + 0.74 and - 0.35 inch, respectively, while the corresponding runoff-departures were + 0.28 and - 0.27 inch, thus providing a satisfactory check and control of the entire series.

Table 3 makes a practical application of the method of comparing monthly and yearly excess or deficiency of rainfall and runoff. On the Washita River, where published records were very sparse and broken, it was discovered that a daily record had been kept for some 20 years, from which it was possible to derive the several elements constituting the total discharge, namely, through the turbine wheel for the generation of power, over the spillway, through the fishway, and for the later years, through the flood-gateway. The best that can be said for this record is that it makes a fair approach to the standards that would be required for official records and it is consistent with the discharge-data available for stations both upstream and downstream from the Southwestern Power Company Dam near Chickasha, Oklahoma, for such intermittent records as have been published for Anandarko and neighboring stations.

After the disastrous flood of September, 1936, at San Angelo and neighboring stations on the Concho River Drainage-Basin in Texas, it was found necessary to glean hydrologic data from many neighboring stations, even some far distant, in order to provide the necessary background for formulating flood-protection plans and corrective measures. The more pertinent of these data on rainfall and runoff are shown in Tables 4, 5, and 6, which give prominence to both means and maximum quantities as observed. With data tabulated in this manner, it is not difficult to make fair estimates for some of the missing quantities, for example, the maximum rainfall-depths to be expected for five-minute, 15-minute, one-hour, and 24-hour periods; or, for that matter, it might be estimated in the same manner for both monthly and yearly means and maxima; likewise for maximum and average runoff-yields. Supplemental notes as to infiltration-rates for prevailing types of soil on the varying topography were required to round out the basic hydrologic data. These were first transposed from the Spur Experimental Station, Texas, where the same types of soil are encountered, and later confirmed by extensive field-tests.

According to Table 3, the average yearly departures for precipitation and runoff of the Washita River Drainage-Area above the Southwestern Power Company Dam near Chickasha, Oklahoma, were 4.325 inches and 0.532 inch, respectively, while the average rainfall and runoff-

Table 3--Relation of annual precipitation at ten selected stations in Oklahoma, in or near Washita River Basin to observed runoff at Southwestern Light and Power Company's dam some three miles below Chickasha, Oklahoma, 1920 to 1939 (P = depth precipitation; R = depth runoff; dP = departure from mean depth precipitation; dR = departure from mean depth runoff)

Year	Cheyenne		Hammon		Weatherford		Cloud Chief		Hobart		Witchita Nat. Forest	
	P	dP	P	dP	P	dP	P	dP	P	dP	P	dP
	in	in	in	in	in	in	in	in	in	in	in	in
1920	.....	.....	36.81	+11.90	39.06	+ 9.71	36.28	+ 9.11	33.96	+ 7.58	40.60	+11.32
1921	.....	.....	21.77	- 3.14	27.80	- 1.55	28.63	+ 1.46	18.92	- 7.46	22.44	- 6.84
1922	.....	.....	24.63	- 0.28	25.94	- 3.41	25.19	- 1.98	23.11	- 3.27	32.53	+ 3.25
1923	.....	.....	46.00	+21.09	41.70	+12.35	40.24	+13.07	41.88	+15.50	42.63	+13.35
1924	24.88	+ 1.63	23.49	- 1.42	24.99	- 4.36	27.10	- 0.07	23.22	- 3.16	24.98	- 4.30
1925	23.95	+ 0.70	21.04	- 3.87	23.78	- 5.57	23.20	- 3.97	28.03	+ 1.65	29.20	- 0.08
1926	30.21	+ 6.96	33.56	+ 8.65	40.21	+10.86	34.79	+ 7.62	41.29	+14.91	39.96	+10.68
1927	19.82	- 3.43	23.47	- 1.44	27.97	- 1.38	28.68	+ 1.51	22.91	- 3.47	33.93	+ 4.65
1928	31.10	+ 7.85	27.39	+ 2.48	31.49	+ 2.14	30.38	+ 3.21	24.74	- 1.64	24.87	- 4.41
1929	25.67	+ 2.42	25.51	+ 0.60	38.80	+ 9.45	35.07	+ 7.90	32.34	+ 5.96	25.85	- 3.43
1930	22.43	- 0.82	24.77	- 0.14	22.83	- 6.52	22.00	- 5.17	23.54	- 2.84	24.80	- 4.48
1931	26.02	+ 2.77	23.80	- 1.11	32.70	+ 3.35	28.61	+ 1.44	24.58	- 1.80	31.54	+ 2.26
1932	21.28	- 1.97	25.06	+ 0.15	27.89	- 1.46	29.09	+ 1.92	28.31	+ 1.93	34.56	+ 5.28
1933	13.20	-10.05	12.83	-12.08	27.19	- 2.16	16.46	-10.71	21.13	- 5.25	28.51	- 0.77
1934	28.30	+ 5.05	17.54	- 7.37	24.46	- 4.89	20.26	- 6.91	21.48	- 4.90	24.73	- 4.55
1935	25.30	+ 2.05	22.40	- 2.51	26.26	- 3.09	29.71	+ 2.54	29.70	+ 3.32	32.50	+ 3.22
1936	18.24	- 5.01	21.23	- 3.68	26.88	- 2.47	19.89	- 7.28	15.14	-11.24	21.40	- 7.88
1937	17.84	- 5.41	18.71	- 6.20	24.13	- 5.22	23.02	- 4.15	25.26	- 1.12	25.00	- 4.28
1938	22.12	- 1.13	23.13	- 1.78	28.71	- 0.64	23.11	- 4.06	27.26	+ 0.88	26.78	- 2.50
1939	21.64	- 1.61	25.08	+ 0.17	24.13	- 5.22	21.71	- 5.46	20.86	- 5.52	18.80	-10.48
Σ	372.00	.....	498.22	.....	586.92	.....	543.42	.....	527.66	.....	585.61	.....
Aver-age	23.25	.....	24.91	.....	29.35	.....	27.17	.....	26.38	.....	29.28	.....
Years rec-ord	16	.....	26	.....	38	.....	36	.....	36	.....	29	.....
Σ record aver-age	23.25	.....	24.98	.....	28.58	.....	27.55	.....	26.99	.....	30.02	.....

Year	Apache		Carnegie		Chickasha		Union City		ΣP	ΣdP		Aver-age dP
	P	dP	P	dP	P	dP	P	dP		Plus	Minus	
	in	in	in	in	in	in	in	in	in	in	in	in
1920	34.41	+ 1.68	29.67	+ 1.04	30.47	- 1.13	38.94	+ 6.44	320.20	58.78	1.13	+ 6.41
1921	25.26	- 7.47	26.89	- 1.74	27.18	- 4.42	28.77	- 3.73	227.66	1.46	33.35	- 3.88
1922	31.69	- 1.04	28.59	- 0.04	27.49	- 4.11	32.12	- 0.38	251.29	3.25	14.51	- 1.25
1923	48.16	+15.43	41.43	+12.80	47.27	+15.67	50.68	+18.18	399.99	137.44	.....	+15.27
1924	26.72	- 6.01	22.04	- 6.59	23.11	- 8.49	29.35	- 3.15	249.88	1.63	37.55	- 3.59
1925	28.54	- 4.19	29.64	+ 1.01	31.62	+ 0.02	35.29	+ 2.79	274.29	6.17	17.68	- 1.15
1926	37.35	+ 4.62	38.79	+10.16	34.78	+ 3.18	47.06	+14.56	378.00	92.20	.....	+ 9.22
1927	44.33	+11.60	36.09	+ 7.46	46.28	+14.68	36.89	+ 4.39	320.37	44.29	9.72	+ 3.46
1928	42.20	+ 9.47	33.45	+ 4.82	30.61	- 0.99	25.74	- 6.76	301.97	29.97	13.80	+ 1.62
1929	35.25	+ 2.52	32.26	+ 3.63	35.04	+ 3.44	33.34	+ 0.84	319.13	36.76	3.43	+ 3.33
1930	36.07	+ 3.34	25.98	- 2.65	31.65	+ 0.05	29.07	- 3.43	263.14	3.39	26.05	- 2.27
1931	30.65	- 2.08	34.29	- 4.34	30.92	- 0.68	26.93	- 5.57	280.04	9.82	15.58	- 0.58
1932	44.99	+12.26	32.24	+ 3.61	37.34	+ 5.74	37.28	+ 4.78	318.04	35.67	3.43	+ 3.22
1933	32.18	- 0.55	20.29	- 8.34	36.09	+ 4.49	30.98	- 1.52	238.86	4.49	51.43	- 4.69
1934	30.40	- 2.33	22.97	- 5.66	27.31	- 4.29	30.25	- 2.25	247.70	5.05	43.15	- 3.81
1935	32.91	+ 0.18	36.75	+ 8.12	34.14	+ 2.54	31.59	- 0.91	301.26	21.97	6.51	+ 1.55
1936	18.77	-13.96	19.48	- 9.15	20.51	-11.09	24.09	- 8.41	205.63	.....	80.17	- 8.02
1937	23.56	- 9.17	24.50	- 4.13	24.04	- 7.56	21.30	-11.20	227.36	.....	58.44	- 5.84
1938	30.86	- 1.87	25.02	- 3.61	32.29	+ 0.69	33.32	+ 0.82	272.60	2.39	15.59	- 1.32
1939	20.36	-12.37	22.27	- 6.36	23.77	- 7.83	26.93	- 5.57	225.55	0.17	60.42	- 6.02
Σ	654.66	.....	572.64	.....	631.91	.....	649.92	.....	5,622.96	494.90	494.94	{+44.08 -42.42}
Aver-age	32.73	.....	28.63	.....	31.60	.....	32.50	.....	28.58	24.75	24.75	4.325
Years rec-ord	29	.....	25	.....	35	.....	20	.....	16 to 38	.....	.....	.....
Σ record aver-age	31.75	.....	28.37	.....	30.49	.....	32.50	.....	28.45	.....	.....	.....

Table 3--Concluded

Year	Washita		Ratio
	R	dR	(dP/dR)
	in	in	
1920	1.673	+0.048	+13.35
1921	1.741	+0.116	- 3.34
1922	1.285	-0.340	+ 3.69
1923	2.895	+1.270	+12.02
1924	1.478	-0.147	+24.40
1925	1.519	-0.106	+10.85
1926	2.231	+0.606	+15.21
1927	2.918	+1.293	+ 2.68
1928	2.325	+0.700	+ 2.31
1929	2.049	+0.424	+ 7.85
1930	1.926	+0.301	- 7.54
1931	0.842	-0.783	+ 0.74
1932	1.725	+0.100	+32.20
1933	0.725	-0.900	+ 5.21
1934	1.029	-0.596	+ 6.39
1935	2.075	+0.450	+ 3.44
1936	1.308	-0.317	+25.29
1937	0.815	-0.810	+ 7.21
1938	1.247	-0.378	+ 3.49
1939	0.665	-0.960	+ 6.27
Σ	32.471	+5.308 -5.337	+182.60 --10.88
Average	1.624	0.532	+ 9.13 - 0.54
Years record	20	.....	.....
Σ record average	1.624	(ΣP/ΣR)=17.52	

depths as recorded or as derived from power-plant records were 28.45 and 1.624 inches per year, showing a ratio of 17.52 between rainfall and runoff-depths over the drainage-basin.

Under the heading of "Mean annual depths" of Table 6, it is shown that the corresponding mean yearly depths of rainfall and runoff for the Concho River Basin, Texas, were 21.91 inches and 0.896 inch, respectively, while for the Upper Colorado River of Texas the corresponding depths were 19.24 and 1.590 inches; and for the Lower Colorado River, with its higher rainfall of 30.37 inches yearly, the average annual runoff-depth over the entire basin is shown as 1.554 inches.

No claim is made nor intended to the effect that such gleanings from the broad fields of hydrology can take the place of a bountiful harvest, such as well-planned and evaluated records are now furnishing throughout this country and also in many portions of the civilized world, though seriously curtailed or even disrupted at many stations due to the impact of the present conflict. Under the standards now prevailing among the various Federal bureaus chiefly responsible for the collection and interpretation of basic data concerning water-resources, their conservation and best utilization, and their final application through far-sighted planning, a priceless harvest is now being garnered. For those earlier periods when the demands of pioneering left little time or opportunity for such activities, only scattered, intermittent, often incomplete records of field-observations are available at this time for our guidance. However, the more meager the harvest, the more important do the gleanings become, as is being demonstrated in both scientific and cultivated fields today.

Having spent many years in Federal service, and having been privileged to investigate the most outstanding hydrologic records of this country and also of some foreign parts, the writer has been impressed with the value of even the fragmentary and isolated data derivable from such tablets as the Palermo and Rosetta stones, or the series of carvings along the cliffs near the cataracts of the Nile River, indicating the actual heights attained by the crests of notable floods. Taken in connection with observed or derived rates of channel-scouring throughout the centuries or thousands of years, some pertinent facts have already been developed, and others are gradually emerging from the twilight zone, through the coordinated efforts of geologists, anthropologists, hydrologists, and other scientists.

It is encouraging to note the number of station-records of both rainfall and stream-discharge which include data derived from the early unofficial observations or intermittent notations of voluntary contributors to hydrology and to related physical sciences. Without such early basic data, some of the most outstanding records would be seriously curtailed. While the urgent need for evaluating such unofficial data has been somewhat relieved by the steadily expanding program of responsible bureaus, charged with specific duties covering the hydrologic field, it would seem advisable for them to maintain continuous reconnaissance for the purpose of locating the most promising among the unpublished or unofficial records.

In the course of transforming basic observations, such as gage-heights, into quantitative units, as for the derived data of Table 3 and for the more extensive projects undertaken within the Mississippi River Basin, the writer has recognized and appreciated the reasons for abandonment of earlier attempts at evaluating some of the records. The inherent uncertainties attending those unofficial or even official records obtained under difficult conditions, disregarding some of the standards that are essential for most reliable results, afford recurrent warnings or invitations to withdraw from the maze of unsolved relationships and to devote the time and effort to records of unquestionable meaning and reliability. However, it is much easier to review and to revise than to make the first quantitative determinations, which immediately become the target for all shafts of differing opinions.

Table 4--Summarized precipitation-records, Concho and Colorado river-basins

Station no. or area (1)	Station and drainage-basin (2)	Elevation (3)	Years record: Day or less (4)	Years record: Month and year (5)	Years record: Last year incl. (6)	Mean on days of rain (7)	Maximum observed precipitation: No. minutes 5 (8)	15 (9)	60 (10)	24 hours (11)	Month (12)
		ft				in	in	in	in	in	in
A	Del Rio, Texas, Rio Grande	957	33	33	1938	0.29	0.75	1.78	4.82	8.88	13.71
B	Amarillo, Canadian River	3,657	39	47	1938	0.31	0.62	1.19	1.95	4.16	9.76
C	Abilene, Brazos River	1,726	45	53	1938	0.36	0.67	1.60	3.47	6.78	15.70
1	Ballinger, Colo. River	1,637	...	44	1938	0.50	.....	.....	.....	6.75	16.45
2	Robert Lee, Colo. River	1,850	...	11	1911	.....	.....	.....	.....	.....	8.53
3	Colorado, Colo. River	2,066	...	29	1929	0.43	.....	.....	.....	.....	14.52
4	Snyder, Colo. River	2,450	...	27	1938	0.43	.....	.....	.....	.....	11.27
5	Lamesa, Colo. River	2,500	...	29	1938	0.42	.....	.....	.....	.....	14.19
6	Seminole, Colo. River	3,275	...	15	1938	0.36	.....	.....	.....	.....	10.91
7	Big Spring, Colo. River	2,533	...	41	1938	0.35	.....	.....	.....	.....	12.89
8	Midland, Colo. River	2,779	...	29	1937	0.42	.....	.....	.....	10.75	13.03
D	Spur, Brazos River	2,300	...	27	1938	0.39	0.78	1.30	1.65	.....	12.43
E	El Paso, Rio Grande	3,710	58	70	1938	0.17	0.43	0.90	1.57	6.50	8.18
	Totals	.....	...	455	.....	4.43	3.25	6.77	13.5	43.82	161.57
	Averages	.....	...	35	.....	0.37	0.65	1.35	2.69	7.30	12.43
	Maxima	.....	...	70	.....	0.50	0.75	1.78	4.82	10.75	16.45
9	Garden City, N. Concho	2,634	25	25	1938	0.41	.....	.....	.....	6.25	12.09
10	Sterling City, N. Concho	2,290	14	14	1938	0.59	.....	.....	3.60	5.50	14.70
11	Water Valley, N. Concho	.....	35	35	1938	0.63	.....	.....	.....	6.75	21.00
12	Sanatorium, N. Concho	.....	3	3	1938	.....	.....	.....	.....	6.00	16.93
13	San Angelo, N. Concho	1,847	51	51	1938	0.47	.....	.....	.....	11.75	27.65
14	5 S.C.S. Sta., N. Concho	.....	3	3	1938	0.40	0.60	1.40	2.45	10.10	20.50
15	Knickerbocker, S. Concho	2,050	27	27	1931	0.49	.....	.....	.....	7.87	11.31
16	Paint Rock, Concho River	1,631	...	18	1937	0.48	.....	.....	.....	8.04	17.17
	Totals	.....	...	176	.....	3.47	.....	.....	6.05	62.26	141.35
	Averages	.....	...	22	.....	0.50	.....	.....	3.03	7.78	17.67
	Maxima	.....	...	51	.....	0.63	.....	.....	3.60	11.75	27.65
17	Eden, Colorado River	2,060	5	5	1938	0.52	.....	.....	.....	6.89	19.28
18	Coleman, Colorado River	1,710	...	51	1938	0.58	.....	.....	.....	.....	15.82
19	Brownwood, Colo. River	1,342	...	46	1938	0.48	.....	.....	.....	.....	11.65
20	San Saba, San Saba River	1,712	...	16	1917	0.39	.....	.....	.....	.....	8.63
21	Rochelle, San Saba River	1,670	...	19	1934	0.56	.....	.....	.....	.....	11.74
22	Brady, San Saba River	1,500	...	11	1938	0.49	.....	.....	.....	.....	14.33
23	Fort McKavett, San Saba	2,155	...	49	1937	0.57	.....	.....	.....	5.50	10.97
F	Substa. 14, Rio Grande	2,600	...	16	1938	0.38	.....	.....	.....	.....	14.05
G	Fort Clark, Rio Grande	1,050	...	60	1930	0.50	.....	.....	.....	18.00	23.03
H	Eagle Pass, Rio Grande	743	...	70	1938	0.42	.....	.....	.....	.....	16.38
24	Junction, Llano River	1,714	...	37	1938	0.59	.....	.....	.....	.....	12.32
25	Mason, Llano River	.....	...	10	1882	.....	.....	.....	.....	.....	13.90
26	Llano, Llano River	1,040	...	45	1938	0.44	.....	.....	.....	.....	23.90
27	Fairland, Colo. River	1,000	...	50	1938	0.41	.....	.....	.....	.....	18.23
28	Marble Falls, Colo.	771	...	30	1938	0.51	.....	.....	.....	11.00	17.50
29	Fredericksburg, Pedernales	1,742	...	30	1915	0.50	.....	.....	.....	.....	12.25
30	Morris Ranch, Pedernales	1,800	...	16	1938	0.39	.....	.....	.....	.....	16.82
I	Kerrville, Guadalupe	1,650	...	43	1938	0.39	.....	.....	.....	11.60	19.94
31	Duval, Colo. River	650	...	27	1916	0.55	.....	.....	.....	.....	16.04
32	Austin, Colo. River	531	40	80	1938	0.46	0.59	1.25	1.81	19.03	20.78
33	Hills Ranch, Colo. River	475	...	13	1930	0.44	.....	.....	.....	16.02	18.21
J	San Antonio, S. Antonio	646	54	68	1938	0.32	0.77	1.46	2.83	7.08	14.07
K	Taylor, Brazos River	583	37	43	1938	0.39	0.90	2.53	4.25	23.11	25.87
34	Smithville, Colo. River	332	...	22	1938	0.52	.....	.....	.....	.....	13.15
35	Lagrange, Colo. River	276	...	30	1938	0.41	.....	.....	.....	.....	16.90
36	Columbus, Colo. River	206	...	35	1938	0.49	.....	.....	.....	.....	16.12
37	Rock Island, Colo. River	254	...	9	1907	0.63	.....	.....	.....	.....	13.85
38	Pierce, Colorado River	102	...	32	1938	0.53	.....	.....	.....	.....	13.80
L	Danevang, Palacios	70	...	43	1938	0.58	.....	.....	.....	.....	15.87
39	Bay City, Colorado River	53	...	7	1917	0.57	.....	.....	.....	.....	11.82
40	Matagorda, Colo. River	10	...	29	1938	0.76	.....	.....	.....	15.71	19.09
	Totals	.....	...	1042	.....	14.77	2.26	5.24	8.89	133.9	496.31
	Averages	.....	...	34	.....	0.49	0.75	1.75	2.96	13.39	16.01
	Maxima	.....	...	80	.....	0.76	0.90	2.53	4.25	23.11	25.87

Table 4--Summarized precipitation-records, Concho and Colorado river-basins--Continued

Station no. or area (1)	Annual precipitation			January			February			March		
					Maximum			Maximum			Maximum	
	Minimum (13)	Mean (14)	Maximum (15)	Mean (16)	24 hours (17)	Month (18)	Mean (19)	24 hours (20)	Month (21)	Mean (22)	24 hours (23)	Month (24)
	in	in	in	in	in	in	in	in	in	in	in	in
A	6.79	18.79	37.75	0.54	1.44	4.12	0.72	5.62	5.78	0.88	2.33	2.47
B	11.15	20.87	39.75	0.49	1.34	2.26	0.78	1.89	2.93	0.89	3.13	4.06
C	10.85	24.36	46.43	0.90	1.97	3.10	1.03	2.17	4.07	1.29	2.53	4.36
1	10.69	24.06	50.55	0.87	.....	3.05	1.05	.....	4.55	1.16	.....	4.54
2	10.00	21.74	34.27	0.70	.....	1.57	1.23	.....	4.68	1.19	.....	5.00
3	10.69	21.14	36.80	0.56	.....	2.11	0.76	.....	4.84	1.00	.....	5.05
4	8.15	20.37	35.82	0.55	.....	1.78	0.74	.....	3.01	1.04	.....	3.43
5	3.22	18.34	33.36	0.43	.....	1.40	0.85	.....	5.08	0.81	.....	2.69
6	6.57	15.68	25.12	0.33	.....	1.10	0.79	.....	3.12	0.62	.....	1.63
7	4.80	18.69	35.81	0.47	.....	2.17	0.69	.....	4.20	0.91	.....	3.33
8	5.52	16.33	29.34	0.47	.....	2.68	0.82	.....	4.19	0.60	.....	3.58
D	11.16	21.07	37.53	0.44	.....	1.71	0.83	.....	3.31	0.95	.....	3.91
E	2.22	8.71	21.81	0.43	1.28	1.63	0.45	1.10	5.55	0.31	1.32	2.09
Σ	101.81	250.15	464.34	7.18	.....	28.68	10.74	.....	55.31	11.65	.....	46.14
Av.	7.83	19.24	35.72	0.55	1.51	2.21	0.83	2.70	4.25	0.90	2.33	3.55
Max.	11.16	24.36	50.55	0.90	1.97	4.12	1.23	5.62	5.78	1.29	3.13	5.05
9	5.76	18.75	31.08	0.56	.....	2.05	0.68	.....	3.85	1.05	.....	6.12
10	8.58	22.47	38.44	0.64	1.15	2.90	1.09	1.65	3.55	1.52	1.60	5.55
11	7.88	20.61	35.88	0.75	1.00	4.50	0.88	2.50	3.50	1.19	1.50	5.56
12	20.20	24.97	30.40	0.52	0.66	1.31	0.59	0.82	1.07	1.95	3.10	3.29
13	8.29	21.96	42.12	0.84	.....	5.41	0.94	.....	4.14	0.98	.....	3.99
14	15.68	23.02	35.09	0.93	.....	2.60	0.47	.....	0.77	1.22	.....	1.90
15	9.06	19.03	31.87	0.69	.....	2.97	0.82	.....	3.64	0.85	.....	3.45
16	14.08	24.45	36.76	0.99	.....	2.64	1.26	.....	4.49	1.32	.....	3.66
Σ	89.53	175.26	281.64	5.92	.....	24.38	6.73	.....	25.01	10.08	.....	33.52
Av.	11.44	21.91	35.21	0.74	0.94	3.05	0.84	1.66	3.13	1.26	2.07	4.19
Max.	20.20	24.97	42.12	0.99	1.15	5.41	1.26	2.50	4.49	1.95	3.10	6.12
17	19.88	26.24	34.25	1.79	.....	3.85	1.51	.....	3.20	1.25	.....	4.75
18	13.32	27.84	45.28	1.22	.....	5.09	1.20	.....	5.02	1.42	.....	5.12
19	10.86	26.68	46.00	1.46	.....	5.63	1.24	.....	4.29	1.64	.....	4.15
20	12.93	25.93	33.54	0.65	.....	2.33	1.54	.....	3.88	1.68	.....	4.77
21	11.27	24.74	49.39	1.41	.....	3.92	1.39	.....	5.15	1.82	.....	6.36
22	8.83	25.55	33.79	1.71	.....	4.00	0.98	.....	2.13	1.27	.....	2.22
23	8.51	22.83	37.05	0.91	.....	3.64	1.24	.....	5.56	1.13	.....	4.14
F	11.94	24.48	41.51	0.87	.....	2.95	0.97	.....	3.98	1.31	.....	3.01
G	6.45	22.04	41.60	0.74	.....	5.39	1.02	.....	6.15	1.30	.....	5.65
H	7.03	21.12	44.36	0.69	.....	4.85	0.86	.....	4.82	1.04	.....	6.27
24	9.02	26.31	44.77	1.04	.....	3.60	1.20	.....	4.64	1.53	.....	4.48
25	19.73	27.03	39.50	1.39	.....	4.10	1.33	.....	2.93	1.04	.....	2.85
26	9.91	24.34	49.88	1.18	.....	4.29	1.42	.....	6.40	1.48	.....	6.27
27	14.83	29.15	56.59	1.61	.....	4.72	1.88	.....	7.08	2.29	.....	9.18
28	9.66	29.24	50.81	1.71	.....	5.81	1.62	.....	6.55	1.89	.....	4.02
29	15.83	27.58	47.23	1.23	.....	5.01	1.46	.....	6.55	1.77	.....	5.68
30	15.68	28.23	49.31	1.45	.....	3.56	1.88	.....	4.73	2.04	.....	5.21
I	12.33	29.75	57.57	1.39	.....	4.37	1.42	.....	5.87	1.70	.....	6.17
31	15.80	31.58	47.18	1.46	.....	6.30	1.86	.....	7.12	1.98	.....	5.99
32	15.58	33.76	64.68	2.18	3.38	9.13	2.39	2.85	9.41	2.39	3.00	7.20
33	13.57	34.42	60.79	2.22	.....	5.43	2.17	.....	6.20	2.36	.....	7.05
J	10.11	27.84	50.30	1.45	2.34	5.86	1.69	3.38	7.88	1.91	2.63	5.91
K	14.59	31.71	51.52	2.07	2.39	8.15	2.10	3.12	7.08	2.10	2.52	6.82
34	16.49	36.27	54.73	3.12	.....	9.43	2.52	.....	7.04	2.96	.....	7.04
35	17.37	38.49	54.60	3.39	.....	11.67	2.64	.....	7.19	3.02	.....	7.73
36	15.92	38.88	64.42	2.75	.....	9.14	2.65	.....	7.21	2.95	.....	11.54
37	22.46	39.77	56.26	2.25	.....	5.46	2.69	.....	7.74	2.62	.....	6.86
38	20.54	40.30	57.29	2.83	.....	9.89	2.63	.....	6.93	2.96	.....	10.05
L	22.00	40.92	64.92	2.68	.....	9.11	2.54	.....	6.59	2.77	.....	7.76
39	25.52	37.46	52.43	0.95	.....	1.71	2.42	.....	5.71	1.66	.....	3.42
40	12.56	40.87	65.89	2.55	.....	6.50	2.45	.....	6.53	2.48	.....	11.21
Σ	440.52	941.65	1547.44	52.35	.....	174.69	54.91	.....	181.56	59.76	.....	188.88
Av.	14.21	30.37	49.92	1.69	2.70	5.64	1.77	3.12	5.86	1.93	2.72	6.09
Max.	25.52	40.92	65.89	3.39	3.38	11.67	2.69	3.38	9.41	3.02	3.00	11.54

Table 4--Summarized precipitation-records, Concho and Colorado river-basins--Continued

Station no. or area (1)	April			May			June			July		
	Mean	Maximum		Mean	Maximum		Mean	Maximum		Mean	Maximum	
		24 hours	Month		24 hours	Month		24 hours	Month		24 hours	Month
	(25)	(26)	(27)	(28)	(29)	(30)	(31)	(32)	(33)	(34)	(35)	(36)
	in	in	in	in	in	in	in	in	in	in	in	in
A	1.48	2.52	4.61	2.42	3.95	8.91	2.29	8.88	13.71	2.17	5.38	8.89
B	1.59	2.68	5.47	3.00	3.86	9.14	2.75	3.88	9.76	2.64	3.14	7.04
C	2.62	1.63	9.80	4.13	6.78	12.03	2.62	4.03	8.40	1.96	3.81	7.95
1	2.51	.....	7.53	3.55	.....	9.24	2.52	.....	10.85	1.95	.....	7.19
2	2.08	.....	8.53	2.92	.....	6.48	2.25	.....	5.48	1.71	.....	5.98
3	2.68	.....	12.31	2.72	.....	7.24	2.20	.....	6.81	2.49	.....	14.52
4	2.25	.....	8.03	2.81	.....	6.00	2.05	.....	7.05	1.80	.....	6.35
5	1.51	.....	8.67	1.97	.....	6.31	2.51	.....	10.30	1.87	.....	5.32
6	0.95	.....	4.31	1.88	.....	5.49	1.63	.....	4.47	2.02	.....	8.25
7	1.87	.....	12.77	2.59	.....	10.10	2.02	.....	6.83	1.95	.....	12.89
8	1.44	10.75	9.77	2.21	.....	7.34	1.84	5.51	6.68	1.67	.....	6.18
D	1.92	.....	7.65	2.82	.....	12.43	2.41	.....	5.19	1.93	.....	7.37
E	0.24	0.98	2.24	0.31	2.07	2.28	0.63	1.82	2.82	1.73	6.50	8.18
Σ	23.14	.....	101.69	33.33	.....	102.99	27.72	.....	98.35	25.89	.....	106.11
Av.	1.78	4.31	7.82	2.56	4.17	7.92	2.13	4.82	7.57	1.99	4.71	8.16
Max.	2.68	10.75	12.77	4.13	6.78	12.43	2.75	8.88	13.71	2.64	6.50	14.52
9	1.87	.....	7.36	2.22	.....	4.89	2.13	.....	7.18	1.47	.....	4.79
10	1.77	5.00	4.57	3.54	2.85	9.82	2.10	2.70	5.96	2.62	2.15	6.00
11	2.21	5.00	9.75	3.08	6.00	10.25	2.15	5.00	7.25	1.71	2.50	7.38
12	2.53	4.90	5.96	3.29	1.66	4.78	2.83	4.91	7.02	2.21	1.52	4.07
13	1.99	.....	6.54	3.07	.....	13.50	2.10	.....	6.13	2.19	.....	10.26
14	1.73	.....	4.35	3.03	.....	5.67	2.14	.....	4.85	2.49	.....	4.14
15	2.06	.....	9.50	2.36	.....	6.14	1.73	.....	5.25	1.47	.....	4.49
16	1.85	.....	5.22	3.40	.....	6.16	2.27	.....	6.26	2.08	.....	5.02
Σ	16.01	.....	53.25	23.99	.....	61.21	17.45	.....	49.90	16.24	.....	46.15
Av.	2.00	4.97	6.66	3.00	3.50	7.65	2.18	4.20	6.24	2.03	2.06	5.77
Max.	2.53	5.00	9.75	3.54	6.00	13.50	2.83	5.00	7.25	2.62	2.50	10.26
17	1.87	.....	4.69	3.67	.....	6.30	2.16	.....	5.13	4.09	6.89	19.28
18	2.79	.....	10.63	4.06	.....	9.74	2.91	.....	9.08	2.62	.....	10.51
19	3.03	.....	11.65	3.93	.....	9.20	2.62	.....	8.90	1.85	.....	10.97
20	3.34	.....	6.04	3.71	.....	8.10	2.45	.....	8.63	1.93	.....	5.79
21	3.01	.....	11.74	3.06	.....	6.87	2.13	.....	7.18	1.53	.....	6.28
22	2.41	.....	6.39	2.75	.....	6.45	2.65	.....	7.33	2.91	.....	14.33
23	1.62	.....	5.77	2.83	.....	6.77	2.38	.....	9.34	2.21	.....	6.78
F	1.62	.....	4.47	3.44	.....	9.23	2.40	.....	9.93	2.46	.....	12.87
G	1.79	.....	7.45	3.04	.....	13.11	2.63	18.00	22.32	1.79	.....	10.75
H	1.54	.....	8.10	2.94	.....	12.72	2.95	.....	16.38	2.01	.....	7.48
24	2.69	.....	9.30	3.77	.....	9.93	2.96	.....	12.32	2.65	.....	10.00
25	2.48	.....	6.89	3.30	.....	8.94	2.00	.....	7.58	2.88	.....	6.64
26	2.72	.....	8.50	3.43	.....	13.32	2.26	.....	9.79	1.84	.....	10.34
27	3.22	.....	9.59	3.42	.....	8.60	3.08	.....	9.34	2.01	.....	7.66
28	3.15	.....	9.58	3.76	.....	11.04	2.78	.....	8.97	1.80	.....	6.17
29	3.49	.....	10.34	3.42	.....	8.64	2.25	.....	10.03	2.21	.....	6.71
30	2.51	.....	7.87	3.80	.....	11.41	3.37	.....	12.55	2.11	.....	7.04
I	3.10	.....	9.85	3.85	.....	12.82	3.05	.....	11.04	2.70	11.60	15.59
31	4.45	.....	16.04	4.11	.....	11.73	2.73	.....	9.10	2.31	.....	12.04
32	3.51	10.00	19.82	4.37	6.16	14.10	2.60	4.97	9.71	2.35	9.56	12.80
33	3.76	.....	8.67	5.01	.....	14.26	3.24	....	9.17	2.54	.....	13.86
J	2.92	6.78	11.64	3.32	6.11	14.07	2.91	4.16	9.37	2.22	3.40	7.88
K	3.58	9.79	16.18	4.13	4.72	10.34	2.39	4.32	8.84	2.05	6.55	14.37
34	3.95	.....	11.60	4.88	.....	12.95	3.11	.....	11.92	2.68	.....	13.07
35	3.92	.....	10.93	4.70	.....	16.90	2.94	.....	11.42	2.62	.....	11.59
36	3.68	.....	10.29	4.34	.....	16.12	2.89	.....	14.64	3.13	.....	10.75
37	3.70	.....	7.37	4.02	.....	7.73	3.97	.....	12.07	4.85	.....	13.85
38	3.00	.....	7.33	4.25	.....	13.73	3.33	.....	13.80	3.72	.....	10.05
L	3.38	.....	9.60	3.61	.....	15.87	3.71	.....	14.73	4.20	.....	11.55
39	3.22	.....	8.54	4.33	.....	6.90	1.33	.....	2.42	1.87	.....	4.29
40	3.38	.....	9.37	4.38	15.71	19.09	3.46	10.10	16.47	3.30	.....	11.23
Σ	92.83	.....	296.23	117.63	.....	346.98	85.64	.....	329.50	79.44	.....	322.52
Av.	2.99	8.86	9.56	3.79	8.18	11.19	2.76	8.31	10.63	2.53	7.60	10.40
Max.	3.95	10.00	19.82	5.01	15.71	19.09	3.97	18.00	22.32	4.85	11.60	19.28

Table 4--Summarized precipitation-records, Concho and Colorado river-basins--Continued

Station no. or area (1)	August			September			October			November		
	Mean	Maximum		Mean	Maximum		Mean	Maximum		Mean	Maximum	
		24 hours	Month		24 hours	Month		24 hours	Month		24 hours	Month
	(37)	(38)	(39)	(40)	(41)	(42)	(43)	(44)	(45)	(46)	(47)	(48)
	in	in	in	in	in	in	in	in	in	in	in	in
A	1.35	3.36	5.89	2.47	5.45	9.95	2.18	6.36	11.69	1.16	2.87	4.54
B	3.05	4.16	6.76	2.32	3.49	6.42	1.59	2.19	7.34	1.01	3.01	5.09
C	2.11	4.06	15.70	2.78	4.76	10.53	2.57	4.85	10.21	1.31	2.14	5.82
1	1.92	.....	12.54	3.20	6.75	16.45	2.54	.....	15.77	1.47	.....	8.75
2	1.92	.....	4.30	3.00	.....	7.24	2.02	.....	3.64	1.66	.....	6.30
3	2.09	.....	7.82	2.62	.....	8.96	2.04	.....	6.63	1.11	.....	4.58
4	2.20	.....	11.27	2.60	.....	10.60	2.35	.....	6.88	1.01	.....	3.79
5	2.26	.....	14.19	2.40	.....	8.85	2.13	.....	6.84	0.76	.....	3.04
6	2.12	.....	5.12	2.27	.....	10.91	1.85	.....	7.06	0.59	.....	1.82
7	1.97	.....	6.76	2.36	.....	(11.0)	2.07	.....	11.87	1.04	.....	4.01
8	1.81	.....	13.03	2.32	.....	6.47	1.62	.....	5.13	0.73	.....	4.49
D	2.64	.....	8.53	2.93	.....	11.13	2.49	.....	6.53	0.85	.....	3.40
E	1.60	2.45	5.71	1.35	2.07	7.22	0.71	1.84	5.15	0.47	1.00	4.60
Σ	27.04	.....	117.62	32.62	.....	125.73	26.16	.....	104.74	13.17	.....	60.23
Av.	2.08	3.51	9.05	2.51	4.50	9.67	2.01	3.81	8.06	1.01	2.26	4.63
Max.	3.05	4.16	15.70	3.20	6.75	16.45	2.57	6.36	15.77	1.66	3.01	8.75
9	2.92	6.25	12.09	2.44	.....	11.15	1.68	.....	4.55	1.01	.....	2.96
10	2.07	2.20	6.34	2.81	5.50	14.70	2.10	3.02	6.28	0.70	1.15	2.00
11	1.74	4.50	7.25	2.34	6.75	21.00	2.29	4.50	7.69	1.31	1.50	6.50
12	0.89	0.85	1.77	5.97	6.00	16.93	1.95	1.37	2.56	0.85	1.00	1.00
13	2.40	.....	14.03	2.97	11.75	27.65	2.10	.....	8.02	1.29	.....	7.02
14	0.37	.....	1.41	6.75	10.10	20.50	1.56	.....	2.43	0.72	.....	1.12
15	2.30	7.87	11.31	2.21	.....	5.99	2.38	.....	5.47	1.22	.....	4.56
16	1.76	.....	6.23	3.51	8.04	17.17	3.37	.....	17.00	1.39	.....	4.21
Σ	14.45	.....	60.43	29.00	.....	135.09	17.43	.....	54.00	8.49	.....	29.37
Av.	1.81	4.33	7.55	3.63	8.02	16.89	2.18	2.96	6.75	1.06	1.22	3.67
Max.	2.92	7.87	14.03	6.75	11.75	27.65	3.37	4.50	17.00	1.39	1.50	7.02
17	1.23	.....	3.45	4.23	.....	13.02	1.64	.....	3.10	1.11	.....	2.25
18	2.47	.....	14.39	3.38	.....	15.82	2.48	.....	14.95	1.69	.....	10.10
19	1.95	.....	7.46	2.97	.....	10.55	2.38	.....	8.63	1.94	.....	9.83
20	1.62	.....	5.77	2.57	.....	4.38	2.60	.....	5.64	2.51	.....	8.42
21	1.91	.....	5.54	3.35	.....	10.92	2.24	.....	9.80	1.50	.....	3.70
22	2.52	.....	6.63	2.45	.....	5.92	2.37	.....	7.22	1.52	.....	3.87
23	2.16	.....	7.54	3.44	5.50	10.97	2.33	.....	10.34	1.42	.....	5.09
F	1.90	.....	8.92	4.14	.....	14.05	2.44	.....	12.80	1.16	.....	4.04
G	1.97	.....	8.55	3.03	.....	11.06	2.12	.....	16.17	1.25	.....	6.67
H	2.17	.....	9.10	3.16	.....	12.24	1.71	.....	7.68	1.08	.....	3.70
24	1.78	.....	7.67	3.26	.....	11.44	2.51	.....	9.45	1.62	.....	7.75
25	3.22	.....	13.90	4.35	.....	10.39	2.02	.....	4.46	1.22	.....	3.90
26	1.69	.....	7.53	2.50	.....	14.45	2.52	.....	23.90	1.74	.....	6.50
27	2.10	.....	7.87	2.81	.....	18.23	2.41	.....	8.36	2.10	.....	9.80
28	1.95	.....	6.54	3.26	11.00	17.50	2.75	.....	8.35	2.10	.....	5.89
29	2.29	.....	8.01	2.83	.....	12.25	2.46	.....	6.71	2.39	.....	11.72
30	1.78	.....	11.31	2.83	.....	16.82	2.84	.....	11.31	1.56	.....	3.99
I	2.02	.....	14.34	3.59	.....	19.94	2.63	.....	11.52	2.23	.....	11.85
31	1.90	.....	6.65	2.34	.....	7.23	3.11	.....	8.50	2.48	.....	9.26
32	2.12	3.56	10.88	3.68	19.03	20.78	3.03	6.95	12.63	2.46	2.90	7.99
33	1.03	.....	3.63	3.71	16.02	18.21	4.01	.....	11.90	2.29	.....	4.68
J	2.13	4.51	9.09	3.17	6.83	11.71	2.18	7.08	8.86	2.00	2.95	9.16
K	1.96	4.78	9.13	3.23	23.11	25.87	2.89	7.52	9.06	2.49	3.99	9.83
34	1.45	.....	4.60	2.92	.....	7.23	3.27	.....	13.15	2.50	.....	6.00
35	2.37	.....	6.47	3.03	.....	10.02	3.59	.....	12.61	2.69	.....	6.78
36	2.44	.....	9.20	3.23	.....	11.55	3.53	.....	11.07	3.37	.....	9.26
37	2.61	.....	7.45	2.78	.....	6.61	3.32	.....	5.90	4.07	.....	12.46
38	3.03	.....	10.39	3.94	.....	10.03	3.19	.....	9.84	3.33	.....	10.04
L	3.09	.....	10.80	3.98	.....	11.97	3.83	.....	9.60	3.13	.....	14.12
39	5.18	.....	11.34	4.03	.....	11.82	4.41	.....	9.39	3.34	.....	7.20
40	2.81	.....	10.93	4.63	.....	17.52	3.70	10.92	15.71	3.31	.....	13.53
Σ	68.91	.....	265.08	102.82	.....	400.50	86.51	.....	318.61	67.60	.....	239.38
Av.	2.22	4.28	8.55	3.32	13.58	12.92	2.79	8.18	10.28	2.18	3.28	7.72
Max.	5.18	4.78	14.39	4.63	23.11	25.87	4.41	10.92	23.90	4.07	3.99	13.53

Table 4--Summarized precipitation-records, Concho and Colorado river-basins--Concluded

Station no. or area (1)	December			Minimum year (52)	Maximum		
	Mean month (49)	Maximum 24 hours (50)	Maximum Month (51)		Year (53)	Month (54)	Day (55)
	in	in	in				
A	0.82	1.42	3.93	1933	1914	June 1935	Feb. ... 1921
B	0.75	2.60	2.88	1910	1923	June 1923	Aug. 13, 1928
C	1.32	4.57	6.69	1917	1932	Aug. 1914	May 23, 1908
1	1.31	.....	4.60	1917	1935	Sep. 1935	Sep. 17, 1936
2	1.06	.....	2.99	1910	1854	Apr. 1908	.....
3	0.80	.....	4.57	1916	1919	July 1902	.....
4	0.96	.....	4.10	1917	1932	Aug. 1920	.....
5	0.83	.....	3.20	1917	1932	Aug. 1920	.....
6	0.63	.....	2.36	1934	1926	Sep. 1936	.....
7	0.74	.....	2.92	1917	1919	July 1902	.....
8	0.80	.....	3.51	1917	1920	Aug. 1920	Apr. 19, 1888
D	0.83	.....	2.56	1924	1926	May 1914	.....
E	0.47	1.48	3.94	1891	1856	July 1881	July 9, 1881
Σ	11.40	.....	48.25	.....	.....	.....	.....
Av.	0.88	2.52	3.63	.....	.....	.....	.....
Max.	1.34	4.57	6.69	1891	1935	Sep. 1935	Feb. ... 1921
9	0.72	.....	2.72	1917	1932	Aug. 1914	Aug. 24, 1934
10	1.51	3.15	5.45	1933	1932	Sep. 1936	Sep. 17, 1936
11	0.96	1.25	5.81	1917	1932	Sep. 1936	Sep. 16, 1936
12	1.39	0.79	2.32	1937	1936	Sep. 1936	Sep. 17, 1936
13	1.09	.....	5.96	1917	1882	Sep. 1936	Sep. 15, 1936
14	1.60	.....	3.21	1938	1936	Sep. 1936	Sep. 15, 1936
15	0.94	.....	7.69	1917	1906	Aug. 1906	Aug. 6, 1906
16	1.24	.....	3.33	1921	1919	Sep. 1936	Oct. 12, 1930
Σ	9.45	.....	36.49	.....	.....	.....	.....
Av.	1.18	1.73	4.56	.....	.....	.....	.....
Max.	1.60	3.15	7.69	1917	1882	Sep. 1936	Sep. 15, 1936
17	1.68	.....	4.05	1931	1938	July 1938	July 23, 1938
18	1.54	.....	8.42	1917	1935	Sep. 1900	.....
19	1.69	.....	5.29	1921	1919	Apr. 1922	.....
20	1.33	.....	3.58	1901	1914	June 1909	.....
21	1.21	.....	3.10	1917	1919	Apr. 1922	.....
22	2.01	.....	5.04	1893	1888	July 1938	.....
23	1.18	.....	6.24	1893	1923	Sep. 1874	Sep. 6, 1932
F	1.63	.....	4.67	1934	1935	Sep. 1935	.....
G	1.25	.....	23.03	1893	1857	Dec. 1857	June 15, 1899
H	0.98	.....	6.61	1893	1900	June 1936	.....
24	1.26	.....	6.13	1917	1919	June 1935	.....
25	1.80	.....	6.70	1879	1880	Aug. 1860	.....
26	1.56	.....	5.94	1910	1919	Oct. 1907	.....
27	2.20	.....	8.44	1917	1919	Sep. 1936	.....
28	2.48	.....	11.46	1917	1919	Sep. 1921	Sep. 10, 1921
29	1.78	.....	7.27	1901	1880	Sep. 1880	.....
30	1.86	.....	4.81	1933	1935	Sep. 1926	.....
I	2.05	.....	5.91	1917	1919	Sep. 1936	July 14, 1900
31	2.85	.....	13.09	1893	1900	Apr. 1915	.....
32	2.63	6.34	16.14	1917	1919	Sep. 1921	Sep. 10, 1921
33	2.08	.....	6.00	1917	1919	Sep. 1921	Sep. 10, 1921
J	1.92	2.59	7.27	1917	1919	May 1933	Oct. 1-2, 1913
K	2.72	6.62	11.74	1917	1919	Sep. 1921	Sep. 9, 1921
34	3.18	.....	7.27	1917	1919	Oct. 1925	.....
35	3.57	.....	8.42	1917	1919	May 1936	.....
36	3.93	.....	9.87	1917	1926	May 1929	.....
37	2.89	.....	6.21	1901	1900	July 1903	.....
38	4.09	.....	9.54	1917	1914	June 1919	.....
L	4.00	.....	14.10	1917	1900	May 1929	.....
39	4.72	.....	10.03	1910	1913	Sep. 1913	.....
40	4.42	.....	11.52	1917	1919	May 1911	May 1, 1911
Σ	72.48	.....	257.89	.....	.....	.....	.....
Av.	2.34	5.18	8.00	.....	.....	.....	.....
Max.	4.72	6.62	23.04	1893	1919	Sep. 1921	Sep. 9, 1921

Table 6--Runoff-characteristics, Concho and Colorado river-systems, Texas

(Data in parentheses include unofficial estimates)

No.	Gaging-station	River	Elevation gage-datum	Years of record		Drainage-area, D-A	Average discharge		
				No.	Last		Per second	Per sq. mile	On D-A
			ft			sq. mi.	cfs	cfs	in
00	Near Carlsbad	Grape Creek	.....	....	.....	53	.....	.....	.....
0	Near San Angelo	Pecan Creek	.....	....	.....	81	.....	.....	.....
1	Carlsbad	North Concho	2,000.8	13	1937	1,241	71.7	0.0577	0.784
2	San Angelo	North Concho	1,800.44	16	1931	1,522	48.0	0.0315	0.428
3	Tankersley	Spring Creek	1,874.6	6	1936	734	.....	.....	.....
4	Tankersley	Middle Concho	1,919.5	7	1937	1,128	60.7	0.0538	0.730
5	Christoval	South Concho	2,010.22	7	1937	434	61.3	0.1410	1.910
6	San Angelo	South Concho	1,802.94	7	1937	2,535	200.0	0.0788	1.070
7	San Angelo	Concho	1,776.8	22	1937	4,217	202.0	0.0479	0.650
			.....	....	.....	.....	.....	.....	.....
8	Paint Rock	Concho	.....	22	1937	5,257	267.0	0.0508	0.690
	Summations	.....	.....	....	.....	.....	.....	.....	6.271
	Averages	.....	.....	....	.....	.....	.....	.....	0.896
	Maxima	.....	.....	....	.....	.....	.....	.....	1.910
9	Robert Lee	Colorado	.....	4	1927	4,400	297.0	0.0676	0.916
10	Bronte	Colorado	.....	5	1920	4,480	(284.0)	0.064	0.870
11	Ballinger	Colorado	1,593.94	21	1936	5,340	434	0.0813	1.104
12	Ballinger	Elm Creek	1,617.72	5	1936	458	103.9	0.2265	3.080
13	Brownwood	Pecan Bayou	1,319.2	11	1936	1,614	236	0.146	1.980
14	Milburn	Colorado	1,254.61	11	1934	12,800	830	0.065	0.883
15	Chadwick	Colorado	.....	7	1922	14,600	1,672	0.115	1.560
16	Menard	San Saba	1,865.05	21	1936	1,151	61.5	0.054	0.733
17	San Saba	San Saba	1,152.4	21	1936	3,046	254	0.0835	1.135
18	San Saba	Colorado	1,096.22	6	1936	18,800	2,167	0.1153	1.565
19	Tow	Colorado	.....	11	1934	19,320	1,370	0.0710	0.963
20	Marble Falls	Colorado	.....	10	1926	24,300	2,472	0.1016	1.380
21	Near Junction	North Llano	1,699.9	20	1935	914	68.1	0.0746	1.012
22	Near Junction	Llano	.....	21	1936	1,762	237	0.135	1.830
23	Castell	Llano	.....	12	1936	3,514	428	0.122	1.655
24	Stonewall	Pedernales	1,418.85	10	1934	647	60.2	0.093	1.280
25	Spicewood	Pedernales	624.8	12	1936	1,294	228	0.176	2.388
26	Near Del Valle	Onion Creek	.....	5	1929	337	82.3	0.223	3.030
27	Austin	Colorado	421.86	38	1936	26,350	2,713	0.103	1.400
28	Smithville	Colorado	270.14	6	1936	27,850	3,964	0.1425	1.930
			.....	....	.....	.....	.....	.....	.....
29	Eagle Lake and Columbus	Colorado	139.56	29	1936	29,140	3,489	0.120	1.630
			.....	....	.....	.....	.....	.....	.....
30	Wharton	Colorado	.....	6	1925	29,400	4,010	0.1365	1.850
	Summations	.....	.....	292	.....	.....	25,461	2.5166	34.174
	Averages	.....	.....	13	.....	.....	1,162	0.114	1.554
	Maxima	.....	.....	38	.....	.....	4,010	0.2265	3.08

Table 5--Runoff-characteristics, Concho and Colorado river-systems, Texas--Continued

(Data in parentheses include unofficial estimates)

No.	Maximum recorded discharges for designated periods								
	Yearly averages				Monthly averages				Daily averages per second
	Per second	Per sq. mile	On D-A	Year	Per second	Per sq. mile	On D-A	Month and year	
	cfs	cfs	in		cfs	cfs	in		cfs
00	.....	.....	.....	.....	.....	.....	.....	.....	.....
0	.....	.....	.....	.....	.....	.....	.....	.....	.....
1	336.5	0.273	3.70	1936	4,019	3.24	3.66	Sep. 1936	62,900
2	580.0	0.380	5.16	1936	6,800	4.46	5.05	Sep. 1936	89,000
3	.....	.....	.....	.....	.....	.....	.....	.....	6,300
4	196.3	0.174	2.36	1936	2,195	1.95	2.20	Sep. 1936	25,800
5	207.5	0.478	6.48	1936	2,352	5.41	6.12	Sep. 1936	35,000
6	641.0	0.253	3.43	1936	7,323	2.89	3.27	Sep. 1936	54,400
7	1,200.5	0.285	3.86	1936	13,994	3.32	3.76	Sep. 1936	131,000
...	.....	.....	.....	.....	.....	.....	.....	.....	.....
8	1,473.9	0.280	3.80	1936	17,222	3.27	3.70	Sep. 1936	134,000
Σ	.....	.....	28.79	.....	.....	.....	27.76	.....	.....
Av.	.....	.....	4.11	.....	.....	.....	3.97	.....	.....
Max.	.....	.....	6.48	.....	.....	.....	6.12	.....	.....
9	451.0	0.1025	1.39	1926	2,010	0.457	0.516	Sep. 1925	24,200
10	(740.0)	0.165	2.24	1919	(2,200)	0.490	0.553	June 1919	(19,000)
11	1,084	0.203	2.76	1935	6,806	1.275	1.440	Sep. 1936	54,300
12	249	0.543	7.36	1935	1,155	2.520	2.840	Sep. 1935	17,300
13	775	0.480	6.52	1932	3,940	2.440	2.750	July 1932	80,000
14	1,810	0.1414	1.92	1932	9,880	0.772	0.870	Oct. 1930	67,000
15	3,850	0.2640	3.58	1919	19,400	1.330	1.500	May 1922	88,400
16	267	0.2320	3.14	1936	2,720	2.360	2.665	Sep. 1936	28,300
17	697	0.2290	3.11	1922	4,460	1.470	1.660	Apr. 1922	50,300
18	3,070	0.1635	2.22	1932	30,680	1.633	1.845	Sep. 1936	202,000
19	3,200	0.1656	2.25	1932	14,900	0.770	0.870	Oct. 1930	66,300
20	6,510	0.2680	3.64	1919	27,500	1.130	1.275	May 1922	104,000
21	220	0.241	3.27	1935	1,960	2.150	2.430	Sep. 1932	22,300
22	708	0.401	5.45	1935	5,797	3.280	3.700	June 1935	124,000
23	1,438	0.410	5.56	1935	11,630	3.310	3.740	June 1935	216,000
24	103	0.1596	2.17	1932	751	1.164	1.315	May 1929	15,400
25	685	0.530	7.20	1936	4,368	3.38	3.820	Sep. 1936	68,700
26	194	0.553	7.50	1929	1,770	5.260	5.950	May 1929	30,500
27	7,530	0.286	3.88	1914	42,600	1.620	1.830	Sep. 1936	323,000
28	6,780	0.243	3.30	1935	38,090	1.370	1.545	Sep. 1936	219,000
...	.....	.....	.....	.....	.....	.....	.....	.....	.....
29	9,200	0.316	4.29	1919	36,100	1.240	1.400	May 1922	164,000
...	.....	.....	.....	.....	.....	.....	.....	.....	.....
30	6,420	0.219	2.97	1920	36,100	1.230	1.390	May 1922	74,000
Σ	55,980	6.3153	85.72	.....	304,834	40.6507	45.904	.....	2,358,000
Av.	2,540	0.287	3.90	.....	13,860	1.850	2.087	.....	107,200
Max.	9,200	0.553	7.50	.....	42,600	5.260	5.950	.....	323,000

Table 5--Runoff-characteristics, Concho and Colorado river-systems, Texas--Concluded

(Data in parentheses include unofficial estimates)

No.	Maximum recorded discharges for designated periods						
	Daily averages			Momentary peaks			
	Per sq. mile	On D-A	Date	Per second	Per sq. mile	On D-A	Date
	cfs	in		cfs	cfs	in/hr	
00	.....	.....	.....	31,800	600.0	0.92	.....
0	.....	.....	.....	30,500	377.0	0.58	.....
1	50.68	1.88	Sep. 26, 1936	94,600	76.1	0.12	Sep. 26, 1936
2	58.50	1.97	Sep. 17, 1936	184,000	121.0	0.19	Sep. 17, 1936
3	8.58	0.32	Sep. 17, 1936	23,900	32.6	0.05	Sep. 17, 1936
4	22.73	0.84	Sep. 26, 1936	35,000	31.0	0.05	Sep. 26, 1936
5	80.3	2.90	July 23, 1936	100,000	230.0	0.36	July 23, 1938
6	21.43	0.80	Sep. 17, 1936	111,000	43.4	0.07	Sep. 17, 1936
7	31.10	1.17	Sep. 17, 1936	230,000	54.5	0.084	Sep. 17, 1936
...	.....	.....	.....	(246,000)	58.3	0.089	Aug. 6, 1906
8	25.49	0.95	Sep. 17, 1936	301,000	57.2	0.088	Sep. 17, 1936
Σ	.....	10.825	.....	.....	.....	2.512	.....
Av.	.....	1.353	.....	.....	.....	0.228	.....
Max.	.....	2.90	.....	.....	.....	0.92	.....
9	5.50	0.21	Sep. 6, 1926	32,500	7.38	0.011	Sep. 6, 1926
10	4.23	0.16	July 21, 1919	(23,000)	5.14	0.008	July 21, 1919
11	10.17	0.38	Sep. 18, 1936	75,400	14.1	0.022	Sep. 18, 1936
12	37.80	1.41	Sep. 3, 1935	26,100	57.0	0.088	Sep. 3, 1935
13	49.50	1.87	July 3, 1932	235,000	145.5	0.226	July 3, 1932
14	5.24	0.19	Oct. 14, 1930	76,100	5.95	0.009	Oct. 15, 1930
15	6.05	0.23	Apr. 28, 1922	115,000	7.89	0.012	Apr. 26, 1922
16	24.60	0.92	Sep. 16, 1936	68,600	59.5	0.092	Sep. 16, 1936
17	16.50	0.62	Apr. 26, 1922	57,000	18.7	0.029	Apr. 26, 1922
18	10.74	0.40	Sep. 21, 1936	219,000	11.65	0.018	Sep. 21, 1936
19	3.43	0.13	Oct. 17, 1930	69,900	3.61	0.006	Oct. 17, 1930
20	4.27	0.16	May 1, 1922	(145,000)	5.96	0.009	Apr. 7, 1900
21	24.40	0.91	June 14, 1935	48,100	52.70	0.082	Oct. 6, 1930
22	70.40	2.62	June 14, 1935	319,000	181.0	0.280	June 14, 1935
23	61.50	2.28	June 14, 1935	388,000	110.6	0.170	June 14, 1935
24	24.06	0.90	May 28, 1929	(80,000)	124.0	0.192	Apr. 7, 1900
25	53.10	1.98	June 15, 1935	155,000	120.0	0.186	May 28, 1929
26	90.60	3.37	May 28, 1929	76,000	225.4	0.350	May 28, 1929
27	12.25	0.46	June 15, 1935	481,000	18.25	0.0283	June 15, 1935
28	7.87	0.29	June 16, 1935	305,000	10.95	0.0170	June 16, 1935
...	.....	.....	.....	(420,000)	15.10	0.0234	Dec. ... 1913
29	5.63	0.21	June 19, 1935	177,000	6.07	0.0094	June 19, 1935
...	.....	.....	.....	(250,000)	8.59	0.0133	Dec. 6, 1913
30	2.52	0.94	May 6, 1922	75,000	2.55	0.0039	May 6, 1922
Σ	530.36	20.60	.....	3,916,700	1,217.59	1.8853	.....
Av.	24.11	0.93	.....	163,196	57.3	0.0786	.....
Max.	90.60	3.37	.....	481,000	225.4	0.350	.....

Table 6--Comparison of mean and limiting precipitation on runoff

(Data in parentheses for neighboring stations outside the Colorado River-Basin are for limiting values)

No.	Factor	Mean annual depths for group			Yearly		
		Min.	Av.	Max.	Min.	Av.	Max.
				Concho River-Basin			
1	Precipitation P in inches	18.75	21.91	24.97	30.40	35.21	42.12
2	Runoff R in inches	4.28	0.896	1.91	2.36	4.11	6.48
3	Runoff-factor (P/R) in per cent	2.3	4.1	7.7	7.8	11.7	15.4
				Upper Colorado River-Basin (items 9 to 13)			
4	Precipitation P in inches	16.33	19.24	24.06	25.12	35.72	50.55
5	Runoff R in inches	0.870	1.590	3.080	1.39	4.054	7.36
6	Runoff-factor (P/R) in per cent	5.3	8.3	12.8	5.5	11.4	14.5
				Lower Colorado River-Basin			
7	Precipitation P in inches	22.83	30.37	40.87	33.54	49.92	65.89
8	Runoff R in inches	0.733	1.554	3.03	1.92	3.90	7.50
9	Runoff-factor (P/R) in per cent	3.2	5.1	7.4	5.7	7.8	11.4
				Representative runoff-factors in per cent			
10	Concho River	2.3	4.1	7.7	7.8	11.7	15.4
11	Upper Colorado (headwaters data lacking)	5.3	8.3	12.8	5.5	11.4	14.5
12	Lower Colorado (headwaters data lacking	3.2	5.1	7.4	5.7	7.8	11.4

No.	Maximum recorded depths for designated time-periods								
	Monthly			Daily			Hourly peaks		
	Min.	Av.	Max.	Min.	Av.	Max.	Min.	Av.	Max.
					Concho River-Basin				
1	11.31	17.67	27.65	5.50	7.78	11.75	2.45	3.03	3.60
2	2.20	3.97	6.12	0.315	1.353	2.90	0	0.228	0.92
3	19.5	22.5	22.1	5.7	17.4	24.7	2.0	7.5	25.6
					Upper Colorado River-Basin (items 9 to 13)				
4	8.53	12.43	16.45	6.75	7.30	10.75	(1.57)	2.69	(4.82)
5	0.516	1.620	2.840	0.16	0.80	1.87	0.008	0.071	0.226
6	6.1	13.0	17.3	2.4	11.0	17.4	0.5	2.6	4.7
					Lower Colorado River-Basin				
7	8.63	16.01	25.87	5.50	13.39	19.03	1.81	2.96	(4.25)
8	0.870	2.087	5.95	0.13	0.93	3.37	0.006	0.079	0.350
9	10.1	13.0	23.0	2.4	7.0	17.7	0.3	2.669	8.2
					Representative runoff-factors in per cent				
10	19.5	22.5	22.1	5.7	17.4	24.7	2.0	7.5	25.6
11	6.1	13.0	17.3	2.4	11.0	17.4	0.4	2.6	5.6
12	10.1	13.0	23.0	2.4	7.0	17.7	0.3	2.7	8.2

The main purpose actuating the more or less continuing and persistent efforts at making such evaluations as are dealt with herein, has been to determine whether values are recoverable, at least proportionate to the investment. Undoubtedly, these quests would have been discontinued in their early stages, had the participants and their sponsors not recognized values representing satisfactory dividends.

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DISCUSSION

PHILLIP LIGHT (U. S. Weather Bureau, Washington, D. C.)--Dr. Jarvis is engaged in a worth-while project in attempting to extend and complete the hydrologic record on some of our important river-basins and deserves credit for summarizing the results for use by the engineering public. Some objections may be raised concerning the use of precipitation- and temperature-departures computed from a station-group that varies considerably in number through the period of discharge-record. It is true that the qualitative agreement of relationships of excess and deficiency may not be unduly disturbed. However, the application of these values to the derivation or testing of either discharges or precipitation may be questioned, particularly in the early years when only scattered observations are available.

As the author indicates, there are anomalies between precipitation- and runoff-departures on the Mississippi River Basin which are explained by the unusual areal distribution of rainfall. It is a well-known fact that some portions of the Mississippi Watershed have experienced heavy precipitation in the past for long periods of time while at the same time the remaining area has had a considerable deficiency of rainfall. This situation has occurred in several years during the period of greatest flood-threat, from December to May, which also coincides roughly with the period of major seasonal runoff.

One of the cooperative studies of the Corps of Engineers and the Weather Bureau is entitled, "A meteorological analysis of the possibility of the coincidence of maximum flood discharges from the Ohio, Mississippi, and Missouri rivers." In this report, based on an analysis of the major Mississippi floods since 1882, it is shown that heavy prolonged rainfall is very unlikely to occur simultaneously on the Ohio Region and the Upper Mississippi and Missouri Region. In order for sustained heavy rains to occur on the Ohio River Basin during the winter and early spring, certain meteorological conditions must be fulfilled. One of these conditions is that an extensive cold air-mass must remain fairly stationary over the north-central section of the country. This means that with sustained heavy precipitation over the Ohio River, simultaneous below-normal temperatures and dry weather would prevail over the Missouri and Upper Mississippi. Consequently, a large contribution of runoff, either from rainfall or snow-melt would be precluded. The converse condition also holds true. Intense storm-action during the winter and spring over the northwestern portion of the basin that produces high discharge from the Missouri and Upper Mississippi, would, in all probability, be accompanied by low or moderate discharge in the Ohio River.

R. S. GOODRIDGE (Federal Power Commission, Washington, D. C.)--The gleanings and the publications of Dr. Jarvis, summarizing his findings, make a stimulating contribution to the field of hydrology. These fruits of labor are especially appreciated by those charged with evaluations and forecasts of the probable magnitude of floods for national flood-control programs.

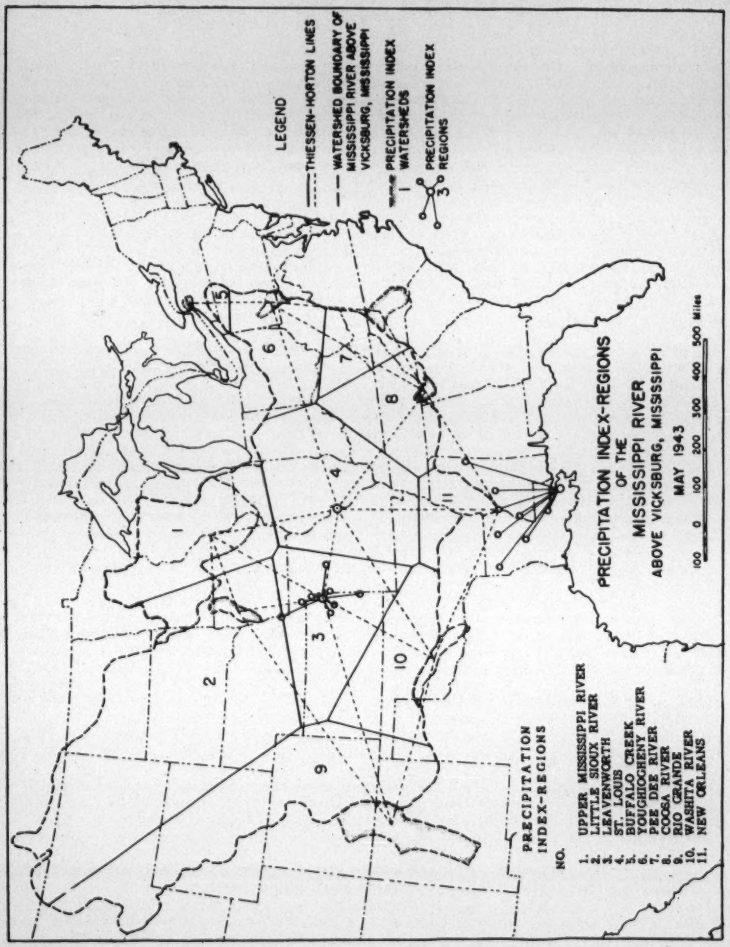
Of his recent major projects, the most comprehensive and daring, and doubtless, the most difficult, has been the effort to reconstruct a record of the flow of the Mississippi River Watershed at Vicksburg, Mississippi, beginning with the year 1817, a record of 125 years through 1942, and the longest in the Western Hemisphere. The drainage-area is 1,144,500 square miles.

The author's contribution reports on the findings of this undertaking, the character of the source-material, with two illustrative diversions to the hydrologic explorations of the Washita and Concho rivers of Oklahoma and Texas, and the sustaining philosophy of his approach--an essential requisite to scientific method.

The objective in this effort, as summarized by Dr. Jarvis, is "to determine whether values (found in such gleanings) are recoverable, at least proportionate to the investment."

Toward this end the writer offers the results of a reconnaissance in the examination of the relative values, indicated by this initial approach, in quest of the degree to which the runoff-indices of this derived record of the annual discharge of the Mississippi River are in agreement with those of precipitation.

Late in 1942, in the course of studies of the runoffs of the Pacific Northwest Region which were correlated with the precipitation of the watershed-areas, the writer was impressed by the remarkable conformity of the results with those derived by F. P. KEEN in his monumental research of the history of precipitation of that region as reflected by the fluctuations of the related records of precipitation, runoff, and tree-rings. Keen's work is published in the Monthly Weather



Review of May, 1937. When arranged to reveal the long secular fluctuations, if any, in the records, the arrays of these studies supported each other and indicated the existence of an approximate 90-year period, especially during the years 1852-1941, and, to a less degree, back to about 1500 [Figs. 7 and 8, ibid.].

Since the record of the Mississippi River, as interpreted by Dr. Jarvis was much longer than that of the Columbia River at The Dalles, Oregon, the writer was eager to make a reconnaissance

examination of the series by similar methods to ascertain the showing relative to trends and the persistencies in excess and deficiency of precipitation.

The writer has prepared 11 index-studies of long-term watershed-precipitation pertinent to the Mississippi River and available to him, with fluctuations as shown on Figure 4 for locations of Figure 1 and listed in Table 1.

Table 1--Regions with annual precipitation-indices, records, length, and area-runoff weights

Watershed or region (1)	Location (2)	First year record (3)	Length through 1941 (4)	No. stations used (5)	Area-runoff weight (6)
			years		
Upper Mississippi River	Le Claire, Iowa	1837	105	20	0.117
Little Sioux River	Above Omaha, Nebraska	1837	105	25	0.075
Leavenworth	Kansas-Missouri	1836	106	9	0.026
St. Louis, Missouri	St. Louis, Missouri	1837	105	1	0.266
Buffalo Creek	West New York	1826	116	19	0.016
Youghiogheny River	Above Pittsburgh, Pennsylvania	1826	116	18	0.117
Pee Dee River	Above Rockingham, North Carolina	1832	110	20	0.090
Coosa River	At Rome, Georgia	1831	111	25	0.126
Rio Grande	Elephant Butte Dam	1850	92	35	0.059
Washita River	Oklahoma, Red River	1837	105	25	0.033
New Orleans	Above New Orleans	1839	103	9	0.075
	Total			204	1.000

Additional fragmentary data of record were available to provide an estimate of a possible set of indices back through 1817, the beginning of the derivation of the Mississippi River flows by Dr. Jarvis. Except for St. Louis, the indices are the composite of the stations selected to the number shown. The base of the indices is the arithmetic average of the 90-year period, 1851-1940.

Having 11 components, the weights to be associated with each were first approached by use of Thiessen-Horton areas and, in turn, reweighted in proportion to the relative runoff of the six principal tributaries of Table 2.

Table 2--Mississippi River components, drainage-areas, mean annual discharges and ratios

Mississippi tributaries (1)	Gaging-station (2)	Drainage-area (3)	Pct total area (4)	Mean annual discharge (5)	Pct total flow (6)	Ratio flow to area (7)
		sq mi	pct	cfs	pct	
Mississippi River	Grafton, Illinois	170,000	14.85	96,700	16.9	1.14
Missouri River	Hermann, Missouri	528,200	46.15	74,000	12.9	0.28
Arkansas River	Little Rock, Arkansas	157,900	13.80	37,200	6.5	0.47
Ohio River	Metropolis, Illinois	164,480	14.38	210,100	36.6	2.55
Tennessee River	Johnsonville, Tennessee	38,520	3.36	64,900	11.3	2.98
Remainder to	Vicksburg, Mississippi	85,400	7.46	90,600	15.8	2.12
Totals, Grafton to Vicksburg		1,144,500	100.00	573,500	100.0	.....

Tables 2 and 3 show the results of the proportional weighting by index watershed-regions. As an example, the weighting for the Upper Mississippi is valued at 0.117, found in Table 3 under column (3). This was obtained by direct proportion, $0.089 \times (0.169/0.128) = 0.117$, where 0.089 is the areal weight, 0.128 is (0.089 + 0.039)--areal weights of Upper Mississippi and St. Louis--associated with the discharge at Grafton, whose flow is 16.9 per cent of the flow at Vicksburg. Similarly, $[0.039\,(0.169/0.128)] = 0.052$ is the weight for St. Louis associated with the flow at Grafton. The weights are expressed in thousandths and were used as decimal multipliers of the component regional indices for the years available. For the years before 1850 proportional weights were accorded by an adjusted distribution. In this manner the index of precipitation is a composite by years summed from the tributary-areas and proportional to the average record flow of the principal tributaries to the Mississippi River at Vicksburg.

Table 3--Areal distribution and weighted tributary flow of the Mississippi River by index watersheds

Watershed or region	Thiessen-Horton areal weight	River and station						Total
		Miss., Grafton	Mo., Hermann	Ark., Little Rock	Ohio, Metropolis	Tenn., Johnsonville	Miss., Vicksburg	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Upper Mississippi	0.089	.117	.....	.....	.....	.....	.....	0.117
Little Sioux	0.284	.....	.075	.....	.....	.....	.....	0.075
Leavenworth	0.096	.....	.026	.....	.....	.....	.....	0.026
St. Louis	0.056	.....	.....	.....	.130	.....	.....	0.266
	0.039	.052	.....	.....	.....	.....	.....	
	0.006	.....	.001	.....	.....	.....	.....	
	0.033	.....	.....	.....	.....	.....	.083	
Buffalo	0.007	.....	.....	.....	.016	.....	.....	0.016
Youghiogheny	0.050	.....	.....	.....	.117	.....	.....	0.117
Pee Dee	0.022	.....	.....	.....	.051	.....	.....	0.090
	0.013	.....	.....	.....	.....	.039	.....	
Coosa	0.022	.....	.....	.....	.052	.....	.....	0.126
	0.025	.....	.....	.....	.....	.074	.....	
Rio Grande	0.100	.....	.027	.....	.....	.....	.....	0.059
	0.063	.....	.....	.032	.....	.....	.....	
Washita	0.065	.....	.....	.033	.....	.....	.....	0.033
New Orleans	0.030	.....	.....	.....	.....	.....	.075	0.075
Total	1.000	.169	.129	.065	.366	.113	.158	1.000

The aggregate yearly departures from the 90-year average (1851-1940) were cumulated and compared with a similar set of departures of the runoffs of the Mississippi River derived by Dr. Jarvis [Proc. Amer. Soc. Civ. Eng., March, 1942]. The plot of the two series are shown on Figure 2.

An inspection of the graph of the cumulated departures of precipitation and runoff reveals certain differences in the trends indicated, especially during the early years preceding 1846, where the trends are in opposition. Since this is evident, views of the backgrounds of both approaches can be made through use of introspection and circumspection. Such appraisal reveals obvious means which may be employed to strengthen the derived segments of the data incorporated with that more dependable. As Dr. Jarvis states, "Usually, a very logical basis will be forthcoming to explain the unusual situation."

Taking the first example used by Dr. Jarvis, he shows that the mean annual depth of precipitation at 15 stations for the year 1844 is indicated to be 0.5 inch below normal, Table 1 of the author [see also, Proc. Amer. Soc. Civ. Eng., March, 1942, p. 432]. The 0.5 inch [-0.52 inch, ibid.] is determined as the difference between the average observed, 41.92 inches, and the "average total record" of 42.44 inches. To look at this more closely, Figure 3 was prepared showing the distribution of the precipitation-stations used by the author. Of the 15 stations, eight are from the Ohio River Basin, two from the Upper Mississippi, two from the Missouri, and three from the Lower Mississippi River. Only two, Leavenworth and Fort Scott, Kansas (the latter, supplemental, not shown on the map nor one of the 50 used by the author for the average, 1893-1938), are west of the Mississippi. This over-representation of the eastern portion tends to indicate an average precipitation in excess of that which would be representative of the basin as a whole. An approximation of the weighted average of the long-term basin average is 38.9 inches. The average for 1844 is about three inches greater or about 108 per cent of the average for the basin. Further, as the author states, there was excessive rainfall over the Kansas Area. This is reflected by the writer's basin-indices. In addition, the indices of the east are indicated to be low. This juxtaposition would serve to show that the 41.92 inches may have been relatively light as the indices from the Washita, New Orleans and through to Buffalo, are from 12 to 24 points below the 90-year average while the indices from the Rio Grande, St. Louis and northerly basins are above the 90-year average from 12 to 47 points. The writer's index is above normal while the author's is below normal. The runoff for 1844 (from Humphreys and Abbot) is given as 4.22 inches above the long-term average of the Mississippi River as derived by Dr. Jarvis. This shows that the weighting used by the writer serves to bring the correlation

closer. It is freely admitted that if the index-watersheds available had not been those of the Rio Grande, Washita, New Orleans, St. Louis (point), Coosa, Pee Dee, Youghiogheny and the Buffalo but those of the Arkansas (1838), North Platta (1849), Upper Missouri (1853), St. Louis (region, 1837), Tennessee (1840), Wabash (1843), Kentucky (1842) and the Upper Ohio (1817) that the agreement with measured values would undoubtedly have been closer. The numerals above are the initial years for which recorded data are continuous. The reconnaissance work for these basins has been done. It is hoped that some future studies will supply such arrays of precipitation-indices.

The plot of the history of precipitation derived for the Mississippi River tends to take a normal pattern in conformity with those available for the United States west of the Middle Atlantic Region, excepting the Coosa, of course. In the background is an entirely independent array of the relative sunspot-numbers arranged similarly. The agreement between the arrays of the precipitation and the relative sunspot-numbers is marked, counting the lag which is normal. Another bit of evidence which bears on the precipitation-history is the contribution of Professor EDWIN LINCOLN MOSELY, of Ohio, who has summarized his extensive studies of the Ohio-Mississippi River Region for the Michigan Academy of Science and Letters (1939) and the Royal Astronomical Society of Canada (1941). He found approximately alternate 45-year periods of excess and deficiency for this region through correlation of precipitation, runoff, and tree-rings. Professor Mosely's tabulations support a period of deficiency previous to 1846. Additional evidence exists with the Tennessee Valley Authority, which has extrapolated a 60-year record of runoff to about 300 years, in an interim report, in collaboration with the universities of New Mexico, Arizona, and Chicago. In a letter regarding the Norris Basin data, Dr. DOUGLASS stated: "Let me add that you have another very important line started, namely, the climatic chronology....." Dr. HAWLEY of Chicago in reporting on "Tree-ring analysis and dating in the Mississippi Drainage" [Univ. Chicago Pub. Anthropology, Occasional Papers, No. 2, April, 1941] quoted from the work of Mr. LASSITER, University of Arizona, as follows:

> "To determine the significance of these approximated values, precipitation-figures were computed from the equations and applied against observed values. The average error between computed and observed values was slightly less than ten per cent over the past 60 years.
>
> "By further computation from the equation, approximate precipitation-figures were carried back 300 years. This span showed several interesting extremes. Drought and wet periods exceeding in duration and extremity observed occurrences were encountered but the average approximated precipitation for the total of 300 years was almost identical to the observed average of 60 years."

Returning to the discussion of Dr. Jarvis' series, one contributing source of possible overestimate of precipitation during the early period, before 1846, and an underestimate subsequently, is revealed in Table 5 of Proceedings of the American Society of Civil Engineers of March, 1942 [pp. 432-433] in which the data of the author's Tables 1 and 2 are given in annual amounts. In fact, Dr. Jarvis states that "the characteristic excess and deficiency relationships seem to hold fairly well, except for the fact that the Great Plains and Rocky Mountain regions seemed to have too great representation in proportion to runoff-yield." Undoubtedly, the use of the absolute values of the annual precipitation of the record-stations for the determination of a running average, instead of a composite in terms of the past 90-year period and weighted in terms of the relative yields from the region of the record-stations, has placed the evaluations in an unbalanced relationship.

It will be noted that the average precipitation ranged from 42.13 inches to 34.73 inches (1893-1938) while 33.66 inches were used for the period 1880-1883. Initially the stations were all from the relatively humid region. As the stations of the relatively sub-humid and arid stations became available the average dropped. The northern Great Plains stations approximate 13 inches and the average dropped out of proportion to the relationship defining the excess or deficiency.

The author's concern over the distribution of the precipitation-stations, shown on Figure 3, suggested Table 4.

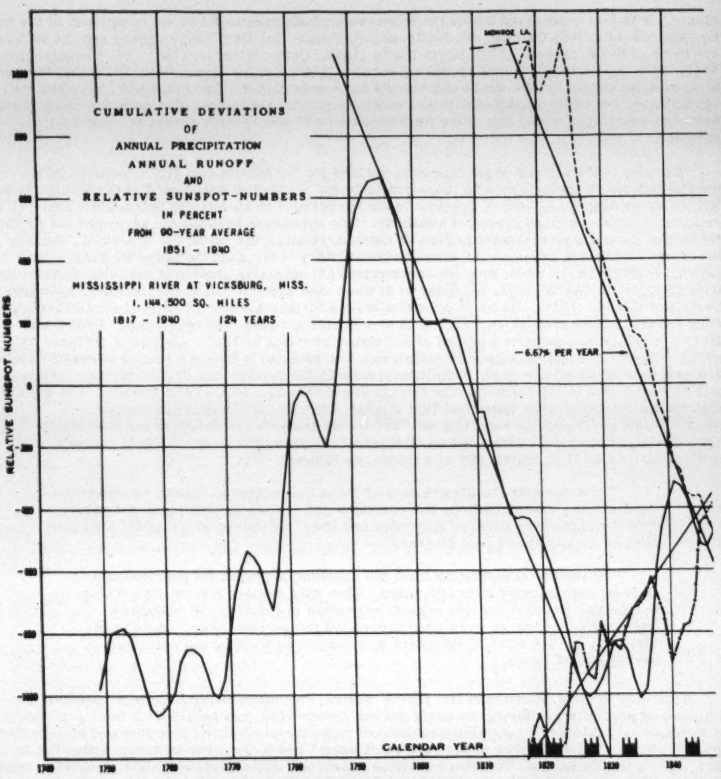


Table 4--Distribution of precipitation-stations, areal-yield ratio, and annual precipitation by tributaries

Line	Mississippi tributaries	Distribution precipitation-stations		Per cent of flow	Ratio [(4)/(5)]	USWB average annual precipitation
		No.	Pct			
(1)	(2)	(3)	(4)	(5)	(6)	(7)
			pct	pct		in
1	Upper Mississippi, Grafton	11	22	16.9	1.30	30.9
2	Missouri, Hermann	14.5	29	12.9	2.25	20.7
3	Arkansas, Little Rock	2.5	5	6.5	0.77	29.7
4	Ohio, Metropolis	10	20	36.6	0.55	42.5
5	Tennessee, Johnsonville	6	12	11.3	1.06	51.7
6	Remainder, Vicksburg	6	12	15.8	0.76	48.8
7	Totals	50	100	100	.....	.....
8	Basin areal normal: Corps of Engineers and Weather Bureau, 1937					30.1
9	Basin weighted normal in terms of tributary-flows					38.9

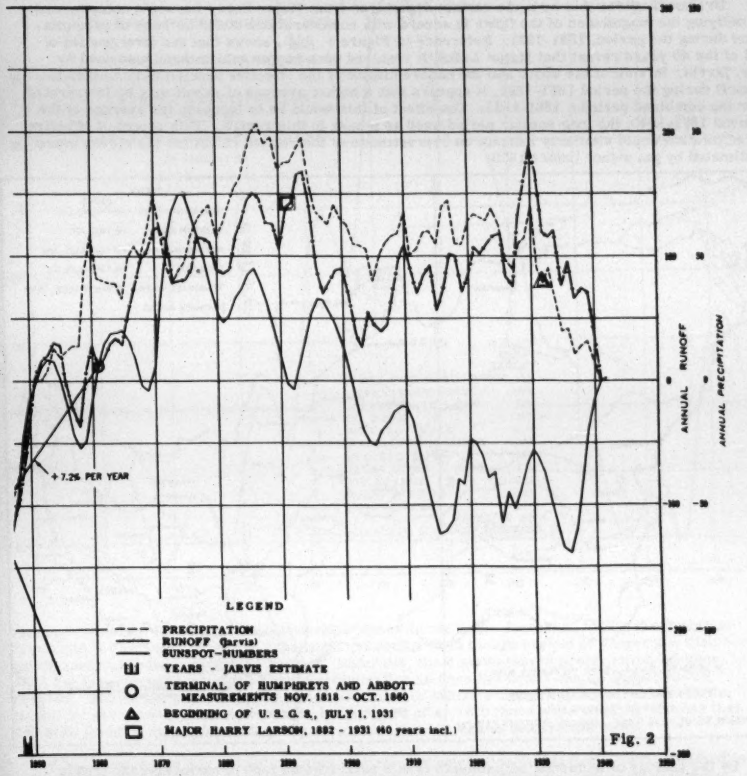

+7.25 PER YEAR
LEGEND
PRECIPITATION
RUNOFF (Jarvis)
SUNSPOT-NUMBERS
YEARS - JARVIS ESTIMATE
TERMINAL OF HUMPHREYS AND ABBOTT MEASUREMENTS NOV. 1818 - OCT. 1860
BEGINNING OF U. S. G. S., JULY 1, 1931
MAJOR HARRY LARSON, 1892 - 1931 (40 years incl.)
ANNUAL RUNOFF
ANNUAL PRECIPITATION

Fig. 2

The ratio of the distribution of the stations in per cent, by the component basins of the Mississippi River, to the relative yield of the basins in per cent, as shown in Table 4, serves to evaluate the degree to which the disproportionate representation of the precipitation-stations may influence the results, when dependence or guidance was obtained from the indicated deficiency or excess of precipitation.

The next question is: To what extent was dependence or guidance obtained from the absolute and unweighted departures? Reference is made to the Proceedings of the American Society of Civil Engineers for March 1942 [pp. 422-426] and to Figure 2 of this discussion, where the major sources of the runoff-evaluations are set forth in the legends, in part, as follows:

1817, through 1860: Humphreys and Abbot, with 11 years estimated by Dr. Jarvis
1861, through 1871: (a) Derived and estimated gage-heights at Natchez, Mississippi
(b) Monthly maximum gage-heights at St. Louis, Missouri
(c) Flood-peaks at Pittsburgh, Pennsylvania
(d) High- and low-river stages at Cincinnati, Ohio
1872, through 1891: Observed river-stages at Natchez, Mississippi (Parts 1858-59)
1892, through 1931, June 30: Major Harry Larson, University of Iowa thesis
1931, July 1 to date: United States Geological Survey

Dr. Jarvis states that he made certain departures from Major Harry Larson's compilations, modifying the magnitudes of the flows in accord with considerations added to those of precipitation during the period, 1891-1931. Reference to Figure 1, ibid., shows that the divergencies of 15 of the 40 years reveal that Major LARSON resolved upon higher values than those used by Dr. Jarvis. In view of the above and the underestimate of the effective precipitation related to runoff during the period 1861-1891, it appears that a higher average of runoff may be interpreted for the combined periods, 1861-1931. The effect of this would be to increase the average of the period 1851-1940, the long secular period used as a base in this review. This aspect of effective precipitation would similarly indicate an overestimate of the related runoff for the eleven years estimated by the author before 1850.

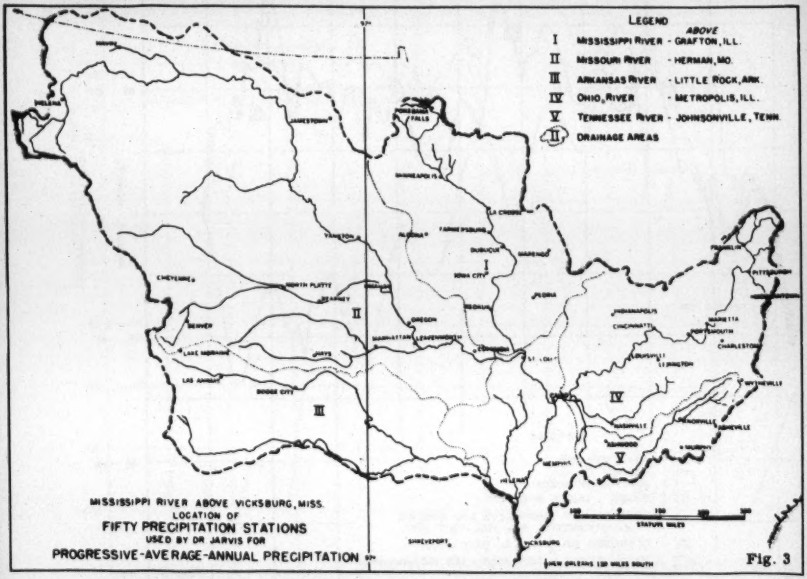
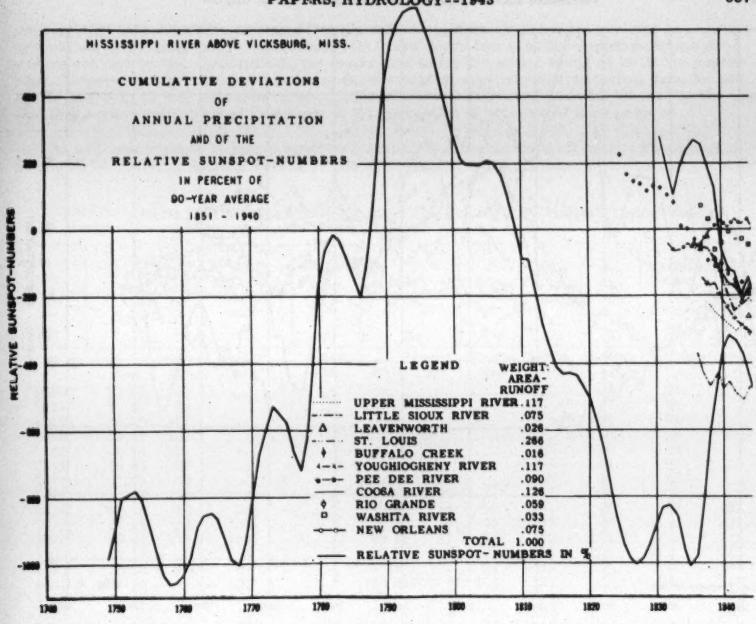


Fig. 3

By the analogy of moments, adjustments of this nature would tend to harmonize the trends shown on Figure 2. Detailed estimates of the degree of the departures, in terms of the precipitation, averaged about 7.5 per cent high before 1846 and subsequently to about 13.5 per cent light, averaging about 7.5 per cent light.

The writer hopes that some agency with resources will carry the gleanings forward after the war. Dr. Jarvis has blazed a trail which aids in the uncovering and evaluation of early hydrologic contributions.

C. S. JARVIS (closure)--The discussion by PHILLIP LIGHT of the United States Weather Bureau points out some of the vulnerable features of the author's approach, and seemingly questions the advisability of applying station-group averages and departures from normal, when the number in the group varies so widely. Specifically, the record starts with a single station in 1817 for precipitation at Marietta (Ohio), a second station is added in 1830, the thirteenth in 1840, the twenty-fourth in 1858, the twenty-seventh in 1867, and the forty-fifth in 1873. Unless such a varying group of station-records contributes something of value, it appears impossible to recover such values as are sought. In the writer's opinion, Mr. Light has suggested the solution of the difficulty, by pointing out that "the qualitative agreement of relationships of excess and deficiency



may not be unduly disturbed." Relationships shown in my Table 1 seem to extend the foregoing remark to the actual quantitative agreement generally, even though neglect of geographic distribution could introduce perplexing results. Naturally, the distribution of precipitation-stations calls for the same degree of care and discrimination as does the actual choice of outstanding records. Before the year 1840, it seemed advisable to utilize practically all available records, except for the unusual number available in Ohio, and after 1870 there were so many stations that the main problem was to keep the truly representative few and to discard the many.

It has been shown that a single station-record of precipitation (at Marietta, Ohio), reduced to successive five-year means, coordinates with discharge of the Mississippi River at Vicksburg, Mississippi, nearly as well as do the large group-records [Proc. Amer. Soc. Civ. Eng., p. 443, March, 1942, in "Early contributions to Mississippi River hydrology].

After devoting considerable portions of many years toward gleaning in the field of hydrology, developing procedures and tests for defining recoverable values, the writer has been impressed with the need for tolerance and suspended judgment for such data as do not readily conform. Further study may disclose the obvious minor defects and lead to such amendments as will make the records acceptable. As an example, early records include a measurement of annual silt or sedimentary deposit at the mouth of the Mississippi River as so many hundred feet high on an area of one square inch, when the context would justify the substitution of "mile" for "inch" as the obvious remedy. There seem to be very few of those early data without definite and recoverable values, even though amendments or corrections may be required. Examples are afforded by the above reference to sedimentation, and also in the body of the paper now under discussion, with reference to CHARLES ELLET's challenge of Lieutenant MARR's estimate or measurement of discharge of the Mississippi River at Memphis, Tennessee. A persistent belief that such data have their values, if the thought is clarified and the ambiguities removed, led the writer to his suggested reconciliation of basic data formerly beclouded or rendered useless by the Ellet-Marr

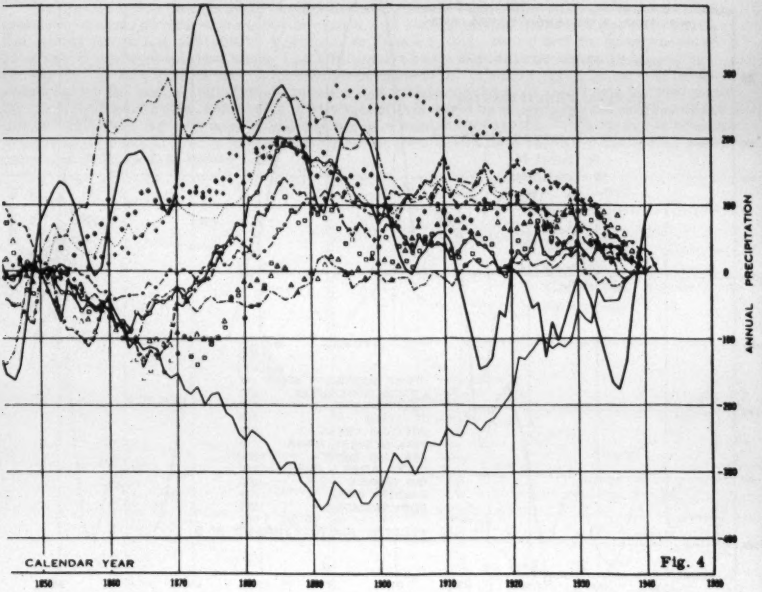


Fig. 4

controversy. Every discordant set of basic data affords a tangible reason for abandoning the search for values; or, approached from a more hopeful view-point, it constitutes a challenge for contest, with identified values as the prize, and increased confidence in logical procedure as an incentive toward further effort.

Probably the most rigorous test of the discharge-quantities as finally adopted by the writer for the 122-year record of the Mississippi River at Vicksburg and Natchez, Mississippi, is to be found in Table 1, wherein the monthly departures of available temperature, precipitation, and runoff from record-means are shown up to 1878, also for five outstanding years of flood or drouth within the period 1926 to 1937, and yearly departures for the remaining portion of the record. The numerous hydrographs of gage-readings along the Mississippi River and its principal tributaries, mainly beginning with 1872, thus provided overlaps of some 11 years into the latter half of the 122-year record, thus permitting a comparison of results derived on monthly and yearly bases.

Inasmuch as more than 90 per cent of the departures as shown in Table 1 show fair agreement between rainfall and runoff, when the factors of abnormal temperature and time-lag in stream-flow, flood-rises, and peaks are taken into account, it seemed that the hydrologic series from 1817 to 1938 were beyond serious challenge. After all, the comparison was generally between the officially observed rainfall at important stations, increasing in number progressively and thus moving to new station-group averages, along with runoff-data varying from derivations and estimates from all available records, fragmentary or otherwise, or from official records on a yearly basis, or from semi-official summaries of discharge, and finally, for the latest seven years, official data according to the best known standards.

In the early stages of this project for deriving or estimating the discharge of the Mississippi River at Vicksburg from all pertinent data, no matter how intermittent, fragmentary, and detached, provided only that their authenticity was established, it would have been reassuring and

encouraging, indeed, to have foreseen that the values would check within ten per cent or less if approached on an independent basis of analysis. Now that it has been accomplished by the procedure outlined by Mr. GOODRIDGE, the easier course for the writer would be to let the matter rest. However, in the search for facts, or for the nearest approximation to factual data, we are not at liberty to choose the easier course, but are bound to follow out in detail all reasonable clues that may lead to refinement of results or to the correction of errors that have crept in.

As will appear later, it seems incumbent upon us to examine the most prominent records of precipitation covering the first decade or two of the period under consideration.

Table A--Annual recorded precipitations and indices in per cent of mean as assembled by C. A. Schott[a]

Year	Spring Mill near Valley Forge, and Philadelphia[c]		Fort McHenry, Baltimore	Washington, D.C.	Marietta[b]		Boston	New Bedford	New Haven	Brunswick and Albany[d]		Fulton
(1)	(2)		(3)	(4)	(5)		(6)	(7)	(8)	(9)		(10)
	inch	Index, pct	Index, pct	Index, pct	inch	Index, pct	Index, pct	Index, pct	Index, pct	inch	Index, pct	Index, pct
1810	32.66	92	.....	.....	.....	.....	.....	.....	89	63	.....	.....
1811	34.97	98	.....	.....	.....	.....	.....	.....	107	86	.....	.....
1812	39.30	111	.....	.....	.....	.....	.....	.....	100	91	.....	.....
1813	35.63	100	.....	.....	.....	.....	.....	.....	120	84	.....	.....
1814	43.14	121	.....	.....	.....	.....	.....	93	126	108	.....	.....
1815	34.67	97	.....	.....	.....	.....	.....	88	114	61	.....	.....
1816	27.95	79	.....	.....	.....	.....	.....	95	86	73	.....	.....
1817	36.01	101	115	.....	(52.00)	(122)	.....	93	98	88	.....	.....
1818	30.18	85	77	.....	50.92	119	95	87	86	59	63	.....
1819	23.35	66	68	.....	36.30	85	79	85	76	.....	75	.....
1820	39.61	111	101	.....	39.11	92	98	89	104	.....	114	.....
1821	32.18	90	119	.....	43.32	101	82	98	100	.....	143	.....
1822	29.86	84	69	.....	43.38	102	61	90	.....	.....	119	.....
1823	41.85	118	105	.....	(49.34)[f]	(115)[f]	103	129	.....	.....	87	.....
1824	38.74	109	100	78	(53.00)	(124)	80	102	.....	.....	99	.....
1825	29.57[c]	67	62[e]	65	(37.00)	(88)	72	82	.....	.....	.....	.....
1826	35.14[c]	80	73[e]	47[e]	41.60	98	93	118	.....	82[d]	.....	.....
1827	38.50[c]	87	77[e]	70	41.48	97	99	135	116	123[d]	.....	.....
1828	37.97[c]	86	78[e]	63	49.50	116	75	84	118	93[d]	.....	.....
1829	41.85[c]	95	124[e]	115	39.52	93	107	140	.....	94[d]	.....	.....
1830	45.07[c]	102	92[e]	104	37.26	87	99	139	.....	103[d]	.....	.....
Mean, inches	35.63	.....	.....	.....	.....	.....	.....	.....	.....	44.68	.....	.....
To 1867	44.05[c]	.....	42.33	37.52	42.70	.....	44.99	41.42	44.43	40.52	54.31	

[a]Contributions to knowledge, Smithson. Inst., pp. 88-107 and 147-151(1873). [b]Unofficial data are in parentheses. [c]Data at Philadelphia, Pennsylvania. [d]Data at Albany, New York. [e]Data supplied from U. S. Weather Bureau Bulletins W and related publications but not found in Schott's paper. [f]The last three months of the year 1823 had no record; the record means for those months up to 1830 were used, therefore, to complete the year. Schott had used somewhat larger quantities to bring the annual depth of rainfall to 50.08 inches and the index-ratio to 1.17 (or 117 per cent).

Critical examination of Table A discloses the following:

(1) In every available record for the years 1817 and 1818, the rainfall-indices are greater for the former, ranging from six to 38 per cent, and averaging 18 per cent. Therefore, the value for Marietta, Ohio, shown in parentheses because it was derived and estimated by the writer as only three per cent greater than that of 1818, is probably too low if indices from such distant stations have much weight. This is in conflict with Mr. Goodridge's conclusions, based on some of the same records, but routed via the Peedee River Basin, North Carolina, and other peripheral watersheds, with a background of sunspot-trends, all purporting to prove that the writer's estimate of rainfall for those early years were too high. His adoption of arbitrary weightings for the various factors comprising his procedure gave ample opportunity to obscure or to distort the real values, as so often happens with hearsay and indirect evidence.

(2) As mentioned in the footnote of Table A, October to December, 1823, had no record of rainfall. The writer had substituted the means of United States Weather Bureau Bulletin W to the end of 1930, before observing that C. A. SCHOTT had used somewhat higher values, which would have changed the rainfall-index for that year from 115 to 117. Again, the writer's estimate of rainfall appears to be somewhat low in comparison with the official estimate of Mr. Schott.

(3) The available station-indices for the years 1824 and 1825 would indicate that the writer's estimates of rainfall-depths for those two non-record years at Marietta are somewhat high, if dependence can safely be placed on such evidence. However, the same fault is to be found with the actual records of the years 1819, 1822, 1826, and 1828; the indices of far-fetched stations would have inclined toward lower annual rainfall for Marietta, Ohio, in each instance.

Recalling that continuous hydrographs of gage-readings, as well as definite evaluations of yearly discharge, were supplied by HUMPHREYS and ABBOT, and taking into account the runoff-departures for 1824 and 1825 as 1.28 inches and - 0.38 inch, respectively, or in percentage, 18 and - 5.4, the corresponding rainfall-departures of 10.87 and - 5.13 inches, or 26 and - 12 per cent appear to be in about the right proportion [see Table 5, "Early contributions to Mississippi River hydrology," Proc. Amer. Soc. Civ. Eng., p. 432, March, 1942].

(4) After the detailed explanations as above submitted with reference to the only estimates of rainfall for which the writer was responsible, and which seem to have withstood the challenge as to their being 7.5 per cent high, on an average, inasmuch as it was shown that two of them were definitely too low, if in error at all, it seems advisable to clear up the subject of estimates of rainfall and their alleged departures from the trends derived by Mr. Goodridge. Let it be clearly understood that no further estimates of rainfall were made that could measurably affect any of the remaining yearly data. The derivation of an occasional monthly rainfall-depth, within the growing group of precipitation-stations, was always guided by the nearest available station-records. Throughout all of the remaining years of the record, the selected stations furnished definite yearly records of rainfall, from which the corresponding record-means were subtracted to determine the annual departures from normal. No one has claimed that such procedure would necessarily represent the average rainfall or departure over the entire Mississippi River Basin; it was surely representative of the particular stations lisied in the growing group, from year to year. As noted by Mr. Goodridge, the average rainfall for the group of 50 stations shown on Figure 3 attained the value of 34.73 inches, nearly intermediate between the United States Weather Bureau's official depth of 30.1 inches over the entire basin-area, and the 38.9-inch depth derived by Mr. Goodridge by weighting the tributary basins, presumably in accordance with their relative yields per square mile, or per tributary. There is much to recommend the use of the records for the 50 stations, in view of their fairly equitable distribution, in preference to the precipitation-index watersheds and regions as shown on Figure 1.

It is decidedly illogical for Mr. Goodridge to compare the 15-station average rainfall for the year 1844 with the 38.9-inch depth which he had derived from the United States Weather Bureau's 30.1-inch mean for the entire basin. It is even questionable whether the official calculations underlying the Mississippi River Basin means extended back to the year 1844; they are more likely to extend back to the early 1870's, when the United States Weather Bureau was established. From that date forward, the expansion of facilities and the growth of stations were accelerated.

Discussing the rainfall-records of 1844 and their departures from the means, Mr. Goodridge states, "The writer's index is above normal while the author's is below normal." The total difference is about one inch, emphasizing the near-agreement of results by independent and widely differing approaches. Even the comments regarding the unequal distribution of stations geographically seem superfluous, inasmuch as additional stations west of the Mississippi River were non-existent, except for some scattered, fragmentary data of questionable standards. The writer was fully conscious of the defects relating to geographic distribution, and lost no time in correcting the situation, as and when new stations became available. According to Figure 1, many of these were disregarded by Mr. Goodridge, while stations outside the Basin were used.

As illustrations of individual preferences in the process of weighting various factors, consider Mr. Goodridge's Table 4, with its columns and also its lines of data numbered consecutively from 1 to 6. It is proposed to extend this tabulation, as in Table B, to include additional columns, yielding quite different percentages and ratios which seem to have more significance for this problem. In Mr. Goodridge's Table 4 the entries in column (3) are rounded off to 14 and 3 for the Missouri and Arkansas, respectively.

Table B--Illustrations of individual preferences in process of weighting various factors

Line (1)[a]	Flow per column (6)[a] Original (6)[a]	Revised (6r)	Product [(3)[a] × (7)[a]] (8)	Per cent of total depth (9)	Ratio [(9)/(5)[a]] (10)	Yield [(5)[b]/(3)[b]] (11)	Products [(8) × (11)] (12)	[(7)[a] × (5)[a]] (13)
	pct	pct	inch	pct		csm	inch	inch
1	1.30	1.30	340	19.5	1.16	0.570	17.6	5.22
2	2.25	2.17	290	16.6	1.29	0.140	2.9	2.67
3	0.77	0.92	89	5.1	0.78	0.236	7.0	1.93
4	0.55	0.55	425	24.3	0.66	1.28	54.5	15.55
5	1.06	1.06	310	17.7	1.56	1.68	87.0	5.84
6	0.76	0.76	293	16.8	1.06	1.06	51.8	7.72
Σ	6.69	6.76	1,747	100.0	6.51	.....	220.8	38.93[c]
Mean	1.11	1.13	.....	.....	1.085	.....	36.8[d]	.....
Max.	2.25	2.17	.....	.....	1.56	.....	.....	.....
Min.	0.55	0.55	.....	.....	0.66	.....	.....	.....
Range (Max. - min.)	1.70	1.62	.....	.....	0.90	.....	.....	.....

[a]Numbers in parentheses as indicated are from columns of same numbers in R. S. Goodridge's Table 4. [b]Numbers in parentheses so indicated are from columns of same numbers in R. S. Goodridge's Table 2. [c]Weighted mean depth of annual precipitation as derived by R. S. Goodridge. [d]Alternate weighted mean depth of annual precipitation for the Mississippi River Basin.

Specific reasons for preferring the weightings as shown in the additional columns for Table 4 include:

(1) Recognition of the stations of high precipitation, instead of balancing them against a like number of stations with much less; for example, 51.7 inches for the Tennessee River Basin against 20.7 inches for the Missouri River Basin. The range of variation in column (9) above is only 0.90 in contrast with 1.70 or 1.62 of column (5), indicating that the geographic distribution is more satisfactory than the original Table 4 had shown.

(2) By way of comparison only, and with no claim for superiority, columns (10) and (11) were added to determine the weighted mean annual precipitation from the runoff-yield in second-feet per square mile, designated csm. This proved to be 36.8 inches as compared with the 38.93 determined by Mr. Goodridge.

There is no evident advantage in using either of these weighted means instead of the 30.1 inches as given by the United States Weather Bureau, or the 50-station mean as used by the writer, or the smaller group-means for the earlier years of record. The important thing is to be sure that the group-rainfall departures from the record-means are correctly computed. It would certainly be cumbersome to repeat the weighting process in the course of determining each yearly mean departure; therefore, it might be inadvisable to use either of those weighted means.

Weighting-factors seem to have gone out of control in Tables 3 and 1, to permit one station, St. Louis, to dominate 26.6 per cent of the entire Mississippi River Basin, thus leaving only 73.4 per cent for the remaining 203 rainfall-stations. Considerable clarification is needed before either of those two tabulations would merit acceptance in such an analysis.

It seems questionable to adopt the 90-year periodicity allegedly discovered for the Pacific Coast stations, 1852-1941, and to require that all precipitation-index watersheds and regions be plotted on that basis. By the very nature of the procedure, it requires that all cumulative-trend curves begin and end at zero- or datum-line, and, in a way, imposes an inherent similarity on this account, even though the curves for Leavenworth and Little Sioux of Figure 4 are markedly non-conformists, and the curve for Coosa is in distinct opposition to the majority of trend-curves, including that of sunspot-numbers. It is well to observe that no evidence of a 90-year periodicity appears on that sheet except what was imposed by the actual construction of curves on that basis. The interval between peaks of sunspot-numbers, 1795 to 1874, is 79 years; and between valleys,

either 109 or 101 years up to 1936. Furthermore, recalling that the study of sunspots began with Galileo's first telescope in 1609, along with the discovery of moons of Jupiter, and that the notable strides in the construction of telescopes must have revealed more and more details of centers of commotion from century to century, it seems that such added numbers that have become visible of late years may have disturbed the normal reckoning. According to the report of the United States Coast and Geodetic Survey for 1860 and 1861, the factor used by Professor WOLF to refer their sunspot-numbers to the standard of his telescope was 1.19.

The writer is not a stranger to the literature on sunspots. Yielding to the pressure of some enthusiasts on this subject, he gave space for displaying the sunspot-numbers of Wolf and Wolfer for the 175-year period, 1749-1924, in Figure 2 of Transactions of the American Society of Civil Engineers [see p. 399 of v. 95, 1931], in a paper entitled "Rainfall characteristics and their relation to soils and runoff." He availed himself of the opportunity to test all of the outstanding records among the 820 listed in Table 1 of the same paper. The result was negative, as will be explained briefly below.

(1) Occasional segments of many rainfall-records, if plotted as ordinates against years as abscissas, may synchronize with the rough sine-curve phases of sunspot-numbers, but every example of this sort shows nearly the same lengths of other segments out of phase, or occasionally in opposition.

(2) The only way to establish direct relationship between sunspot-numbers and phenomena of weather seems to be the one in vogue among proponents of this idea--not new, by any means, for it has long been a subject of speculation and controversy. By noting all of the synchronizations, and forgetting or neglecting those out of step, or conveniently bringing them all into the fold on the claim that this one has a lag of seven years, and that one, five years, a pretense of harmony may be established, but it seems to be lacking in the element of truth as sought by the scientific professions.

(3) Not a single year has passed since precipitation-records were widely established, to which we now have access, without realizing some considerable portion of its normal quota of both intense, wide-spread storms, and either localized or regionalized drouths, no matter what phase of the sunspot-numbers and cumulative curves of departures from normal happened to prevail at that time.

(4) Whatever slight differences of the solar constant may appear to be somewhat associated with fluctuations in sunspot-numbers may be nullified or reversed by the mechanics of air-mass movements and the irregularities of rainfall-distribution in any region; therefore, any predictions on such a basis should not be regarded too seriously until some tangible proof has been brought forward.

Of the 11 early years for which Humphreys and Abbot had not published the yearly discharges of the Mississippi River at Vicksburg or Natchez, only the last three (1842, 1943, and 1848) are without substantial segments of gage-reading hydrographs; and for these three, substitution of such hydrographs as those at St. Louis or Memphis, or the Ohio River hydrographs of both gage-readings and monthly discharge at Wheeling, West Virginia, provided valuable clues for guiding the estimates of discharge, month by month, and thus bringing forth the synthetic hydrographs shown in broken lines, incorporating also the monthly runoff as derived from rainfall-data. Naturally, the records of rainfall and their departures from normal, devoid of estimates or weighting-factors, were important elements, although not necessarily dominant where segments of hydrographs at stations on the main river were available and fairly continuous, and where those early approximations to rating-curves were reasonably applicable, as discussed in references cited above.

The alleged errors disclosed by watershed and regional trend-curves of rainfall-indices, along with those curves established by cumulative departures from the 90-year means of sunspot-numbers and tree-ring widths, seem to have originated about equally among the early years of official record, those of unofficial estimates or derivations, those guided entirely by rainfall-runoff relationships (1861 to 1871), those evaluated by the writer from Mississippi River Commission hydrographs and rating-curves (1872 to 1891), those similarly evaluated by Major HARRY LARSON, under the direction of Professor FLOYD A. NAGLER, at the University of Iowa, for submission as a thesis intended for an advanced degree and covering the 40-year period 1892 to 1931, and those of the United States Geological Survey, dating from July, 1931. Some degree of confirmation had been afforded by official daily determinations of discharge for several years

by the Mississippi River Commission, also semi-official discharges for the main river and tributaries, 1901 to 1931. Against such an array of evidence, it appears that the above-mentioned trend-curves seem to lie harmlessly displaying their local and individual differences, or inviting adjustments of their own conflicts and difficulties by some more convincing formula than the overworked "phase-lag."

Acknowledgment is due the scientific staffs of both the Smithsonian Institution and the United States Weather Bureau for their pioneer work introducing the use of rainfall-indices on a percentage basis; also to Mr. Goodridge and his associates on flood-control projects in California for further developing and extending the concept to cover watershed and regional areas. Within their proper scope, such indices are capable of partially bridging many of the gaps and deficiencies in basic hydrologic data, through cautious use of the entire mass of data from neighboring stations. However, as shown by recent studies of the Hydrometeorological Section of the Weather Bureau and the Corps of Engineers, a wide-spread, intense storm over the Ohio River Basin would seemingly preclude like phenomena over the Upper Mississippi River and Missouri River basins. By the same token, the use of trend-curves from such remote drainage-areas as those of the Buffalo River, the Peedee, the Coosa, and the Rio Grande, either with or without statistics of sunspots and tree-rings, is decidedly questionable if intended to accomplish a revision of basic hydrologic data within the Mississippi River Basin, or of well-founded interpretations, derivations, and estimates thereof that have already withstood such cross-checking and comparisons as could be devised from all source-material.

The recently extended stream-gaging facilities of the United States Geological Survey, together with the consistent team-work of the Corps of Engineers and the United States Weather Bureau, acting as a leaven for the mass of earlier data that had lain seemingly inert for so many years, have already accomplished much toward clarifying the basic problems relating to the discharge of the Mississippi River, its regulation, and its ultimate utilization.

INFLUENCE OF TOPOGRAPHY AND SOIL-DEPTH ON RUNOFF FROM FOREST LAND

M. D. Hoover and C. R. Hursh

Introduction

It has been recognized that topography, size, shape, vegetation, and soil-profile differ for individual drainage-areas. These inherent properties of watersheds together with climatic factors are the principal causes for variations in the hydrologic characteristics of different drainage-areas. These properties account for the differences in unit-tributary contributions to the runoff of the larger streams. Few watersheds are uniform within themselves as regards topography, vegetation, and soil-profile, but small watersheds show less variability in these properties and are, therefore, most useful in the study of contributions of tributaries to runoff of larger streams. They are also more useful in the study of the complete water-cycle, and of the changes within the water-cycle resulting from changes in conditions of vegetation and soil brought about through different land-use practices.

Watershed-studies requiring measurements within the water-cycle are now in progress on the Coweeta Experimental Forest in Western North Carolina. The Forest of 4,200 acres ranges in elevation from 2,200 to 5,200 feet, and contains 30 small drainages with continuous flow. Average annual rainfall ranges from 70 to 80 inches depending on elevation and is distributed throughout the year. Mean annual temperature is 55°F at the elevation of 2,200 feet. Natural growth is composed of deciduous forest with abundant shrubs and minor vegetation. Topography is favorable to the establishment of small independent experimental watersheds.

Results to date indicate that watersheds at the Coweeta Experimental Forest may be roughly classified on the basis of elevation. Watersheds lying largely below an elevation of 3,000 feet are characterized by a soil-profile common to the intermountain areas of the Appalachian Region and Piedmont Plateau. The soil-profile shows deep sub-soil horizons. Shallowest soils occur on the upper slopes, but even here depths of soil of four to six feet are common.

Watersheds above 3,000 feet in elevation are typically more steep. On the slopes, depths of soil are generally less than two feet. However, at the foot of these slopes, and along stream-courses, there is an accumulation of a large amount of angular rock-talus and finer material.

These differences in the soil-profile between the lower and higher elevations markedly influence runoff. Characteristics of storage of the deep soil-profiles found on the Coweeta Experimental Forest have been previously discussed [see 1 of "References" at end of paper]. Under natural forest-conditions, infiltration-values are well in excess of occurring rainfall-intensities. The soil-profiles store large quantities of water both as retained soil-moisture and as ground-water. Stream-flow from such areas is subject to a large degree of regulation. A characteristic winter storage of ground-water takes place which sustains ground-water flow well into the growing season. Because no surface storm-flow other than channel-precipitation occurs, peak-rates are comparatively low.

On the higher watersheds, the shallow soils on the slopes have a lower total storage-capacity which is compensated for in part by the high unit-storage of the talus-deposits. Although the latter generally cover only a small portion of any drainage, they contribute considerable storage-capacity. When the soil on these watersheds is wet to field-capacity, water moves down the slope and is stored in the talus-fill. Outflow from this storage occurs at rapid rates because of steep slopes and large voids in the fill-material. This outflow represents a dynamic form of subsurface storm-water and contributes appreciably to the hydrograph during the course of the storm. It is the form of water that accounts for the high unit-rates of storm-discharge that frequently have been reported from mountain forest land.

Higher rates of storm-discharge may be recorded at gaging-stations on the major streams even though the gages are at lower elevations, but these rates are produced by discharge from the tributaries located at high elevations. These upper tributaries not only receive more rainfall, but have less capacity to retain or store rainfall as it occurs. This is illustrated by the peak-discharges recorded at stations Nos. 8 and 9, which gage the two major streams on the Coweeta Experimental Forest (Fig. 1). Total drainage-areas above these gages are 1,877 and 1,788

Fig. 1--The Coweeta Experimental Forest photographed from 12,000 feet [outside boundaries of the forest and of the drainage-areas discussed, are shown in white (photo by Tennessee Valley Authority)]

acres, respectively. For the general storm of December 27-29, 1942, the peak-discharge at gage No. 8 was 56 second-feet per square mile, and at gage No. 9, 55 second-feet per square mile. Tributary-drainages that are at the lower elevation, produced peaks of only 23-31 second-feet per square mile. Working with a hydrograph produced by this general heavy storm from gage No. 8, it might appear logical to assign the peak to the whole drainage-area. Actually, a proportionally much greater rate of discharge occurred from the tributaries at higher elevations. To assign a high unit-discharge based on the entire drainage above gage No. 8 to the lower watersheds would lead to a very erroneous analysis of the hydrologic characteristics of tributaries within different ranges of elevation.

Presentation of Data

Figure 1 shows the Coweeta Experimental Forest photographed from 12,000 feet. Watersheds considered in this discussion are numbered. Watersheds 37, 28, and 22 are representative of the areas of higher elevation, whereas watersheds 1, 7, 10, and 14 represent areas of lower elevation. Differences in runoff from the two classes of drainages are illustrated by the storm of December 27-29, 1942. Rainfall of 6.78 to 10.85 inches produced a uniform pattern over the entire forest. Intensities were remarkedly uniform with an average of 0.15 inch per hour. At no time did the intensity exceed 0.46 inch per hour. These rates greatly eliminated the factor of intensity as being an important factor in producing surface-runoff insomuch as all of the drainage-areas are in natural forest cover, and have surface infiltration-rates far in excess of the maximum intensities of the storm. Antecedent rainfall had been sufficient to satisfy soil-moisture deficiencies and to cause a general rise of the ground-water level. Data for drainage-area and runoff are shown on Table 1.

Table 1--Drainage-area data, storm of December 27-29, 1942, Coweeta Experimental Forest

No.	Area	Elevation		Precipitation			Runoff			
		Minimum	Maximum	Amt.	Maximum	Average	Total	Peak	Prior	Base mdt. Jan. 2
	acres	ft	ft	in	in/hr	in/hr	in[a]	csm[b]	csm[b]	csm[b]
1	40	2,315	3,241	6.78	0.38	0.13	1.60	22.82	1.15	3.62
7	145	2,370	3,510	6.84	0.38	0.13	1.77	24.31	1.36	4.13
10	212	2,436	3,801	7.52	0.38	0.13	2.20	28.36	1.80	5.87
14	152	2,318	3,125	7.03	0.41	0.13	2.33	31.53	1.87	5.64
8	1877	2,292	5,249	8.40	0.46	0.14	4.22	56.43	2.04	6.81
22	88	2,780	4,089	8.37	0.46	0.16	5.04	68.27	2.96	9.62
28	350	3,162	5,097	10.84	0.46	0.16	5.33	83.34	3.29	10.91
37	100	3,390	5,240	10.85	0.42	0.15	8.78	167.36	3.82	10.44

[a]Above prior base, beginning of storm to midnight of January 2, 1943. [b]Second-feet per square mile.

Figure 2 shows the hydrographs produced by this storm for the areas mentioned, together with precipitation-data at intensity-gage No. 4, situated 3,350 feet above sea-level. Precipitation-data at other intensity-gages follow the same pattern as gage No. 4. It will be seen that the discharges for the watersheds with the deeper soil-profiles are all of the same magnitude, illustrating that they are all from the same type of storage. Peak-rates from such areas range from 22 to 31 second-feet per square mile on the tributary drainage-areas. These rates may be compared with peaks of 67 to 167 second-feet per square mile for the higher watersheds, illustrating high outflow rates from temporary storage in the talus-fills. Although the latter peaks are relatively high, the hydrographs show very definite regulation of runoff by detention-storage. Watershed 37, for which the peak was 167 second-feet per square mile, produced a discharge for the six-hour period--from $18^h\ 00^m$ to midnight of December 29--amounting to 0.72 area-inch at a mean rate of 77.57 second-feet per square mile. This period was well after outflow of channel-precipitation was complete. Runoff for the following day, December 30, amounted to 1.32 area-inches, a mean daily flow of 35.3 second-feet per square inch; for December 31, 0.73 inch, a mean daily flow of 19.7. This amount of water appears to have been detained in the same manner as storm-water in a detention-reservoir. The storage and comparatively rapid release of this amount of water appears to be associated with the talus-deposits on the lower slopes and in the bottoms of the ravines.

Characteristic longitudinal stream-profiles for watersheds at different elevations within the belt of high rainfall of the Southern Appalachian Mountain Region are shown in Figure 3, in which

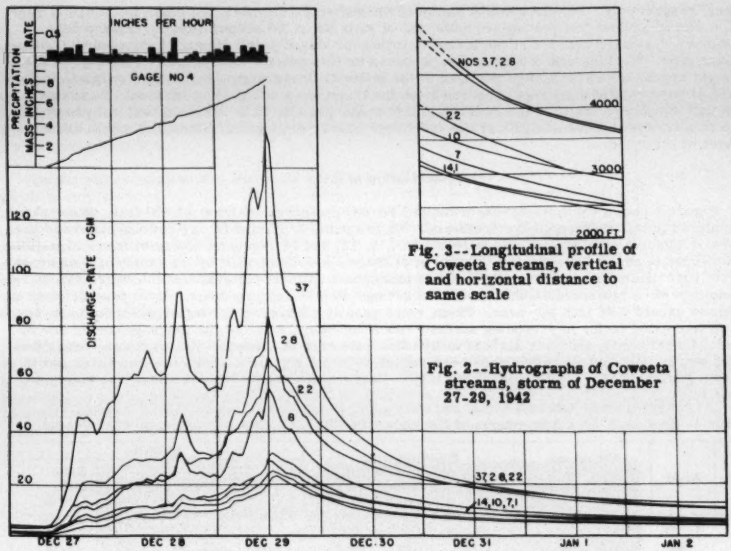


Fig. 2--Hydrographs of Coweeta streams, storm of December 27-29, 1942

Fig. 3--Longitudinal profile of Coweeta streams, vertical and horizontal distance to same scale

the lower stream-reaches for the larger areas are not shown. A very rapid increase in slope takes place in the upper portion of the profile of the higher watersheds. At the base of this slope occur the beds of talus-material that appear to exhibit a definite detention-reservoir effect during storm-periods. The profile of watersheds within the lower ranges of elevation do not exhibit these steep slopes.

In the Southern Appalachians, the amount of rainfall increases with elevation. As a result, watersheds at higher elevations generally have more moisture present and consequently operate with less opportunity for storage than drainages at lower elevations. This may have been an important factor in the storm of December 27-29, but it is not the only factor to be considered. Differences in runoff shown in Figure 2 were apparently also closely related to the soil-profile on the two classes of areas, together with the associated difference in opportunity for storage.

Discussion

By far the greatest amount of land-area in the Southern Appalachian Region is less than 3,000 feet above sea-level. Under natural forest conditions, this land generally contributes only small amounts of storm-runoff to stream-tributaries. When depleted and misused for agriculture and grazing, however, both opportunities for infiltration and storage are greatly reduced, and drainage-areas with these same soil-profiles may produce measured peaks of 800 to 1200 second-feet per square mile for watersheds of 10 to 20 acres.

Most of the land-areas below 3,000 feet in the Southern Appalachian Region are pastured or cultivated, or because of their accessibility have been heavily cut over for wood products, and hence there is very little undisturbed forest-cover. At the higher elevations, however, which are in effect the headwater-areas for the streams, there is much less farming. Particularly the steep slopes have not been used for agriculture because of the shallow soils and difficult cultural technics. In addition, the accumulations of talus, or rock-bars as they are locally called, cannot easily be logged, and consequently trees are more likely to be present, giving the appearance of a heavy forest-cover. Because vegetation has been little disturbed, runoff-characteristics of

streams draining such areas have been considered to represent the effects of a forest-cover. However, on many of these headwater-areas, the geologic factors are expressed in the thin soils and deep talus-slopes in the ravines may be far more important than effects of vegetation. Vegetation actually does have a tremendous influence on the thin soil-profiles on such areas, being directly responsible for the organic material which protects the mineral soil on extremely steep slopes. Without this organic development, it is conceivable that no soil whatever would remain on the steep slopes in the Southern Appalachians and that the talus-fills would be rendered less efficient in producing the controlling effect they now exert. On forested watersheds where peak-discharges are now high, the principal consideration is not the present magnitude of the peaks, but rather what would be the actual runoff-rates if no vegetation were present. In making a comparison of the effect of different land-use types upon runoff, it is obviously necessary that the studies under consideration all be carried out on watersheds of the same general hydrologic characteristics with regard to the nature of the soil-profile.

The remarkable similarity of the unit-discharge rates from watersheds at the lower elevation shown by Figure 2 indicates that these watersheds, although differing in size, shape, and aspect, are controlled principally by the uniform soil-profile type and associated natural forest-cover. Soil and topographic conditions similar to those at the lower elevations of the Coweeta Experimental Forest may be found throughout the Southern Appalachian Mountains and Piedmont Plateau. Preliminary observations indicate that wherever the same general conditions of soil and vegetation-cover exist, there occur similar conditions of high infiltration and storage of rainfall during prolonged storms, such as have been recorded at the Coweeta Experimental Forest. This suggests that the results of studies obtained on the Coweeta Forest at an elevation below 3,000 feet may have a wide application to the land-use problems throughout the deep, red-clay soils of the Southeastern and Middle Atlantic States. The results obtained from watersheds above 3,000 feet apply principally to steeper mountain ranges of the Southern Appalachian Region.

Summary

This paper is a report of tributary-contributions from small drainage-areas to the runoff of larger streams within the Coweeta Experimental Forest. Storm-runoff is discussed for the storm of December 27-29, 1942. This storm--6.78 to 10.85 inches--produced the same general rainfall-pattern over the entire forest. Average intensities were quite low--0.15 inch per hour with maximum 0.46 inch per hour. Small tributary drainage-areas--40 to 212 acres in size--with elevation principally below 3,000 feet, produced maximum peaks of 22 to 32 second-feet per square mile. For drainage-areas of similar size, but with elevation well above 3,000 feet, peaks of 68 to 167 second-feet per square mile were recorded. Difference in peaks is assigned in part to greater rainfall at higher levels, but it is also related to soil-depth, topography, and hydrologic characteristics associated with the different elevations.

References

[1] C. R. HURSH and E. F. BRATER, Separating storm-hydrographs from small drainage-areas into surface- and subsurface-flow, Trans. Amer. Geophys. Union, pp. 863-871, 1941.

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DISCUSSION

WALDO E. SMITH (U. S. Soil Conservation Service, Washington, D. C.)--The authors have presented, in a very interesting and instructive manner a picture of the influences of topography and soil-profile on runoff from a given rain in the forested Coweeta Area. An additional column in Table 1, showing the retention of the rain on all watersheds, would have been revealing, and is shown in Table A.

The first group of watersheds, lying at the lower elevations, all had uniformly high retention as compared with the second group as a whole. However, within the second group there is great variation, and on the largest watershed of the group (No. 28) the retention was the greatest of all the watersheds listed. However, the general trend--relatively low retention on the steep upper watersheds, more on the lower and flatter ones--conforms to the findings of flood-control studies made in the Department of Agriculture to determine the relative retentive qualities of various soil-profiles in the Southeast.

Table A

Watershed No.	Area	Retention determined from Table 1
	acre	inch
1	40	5.18
7	145	5.07
10	212	5.32
14	152	4.70
22	88	3.33
28	350	5.51
37	100	2.07
8	1877	4.18

Rain-gage No. 4, with a total rainfall of about 8.3 inches (Fig. 3), corresponds quite closely with the average rainfall of 8.37 inches on Watershed 22 (Table 1). It is of interest to note that the peak-rate of runoff from Watershed 22 was 68 second-feet per square mile--about 0.1 inch per hour. The rainfall for an hour near the end of the storm just preceding the peak was about 0.3 inch, thus indicating that a balance between rainfall and runoff had not been reached and that detention plus retention was increasing at a rate of about 0.2 inch per hour, or somewhat more, since the peak-rate of runoff did not occur until after the termination of the rainfall-rate of 0.3 inch per hour.

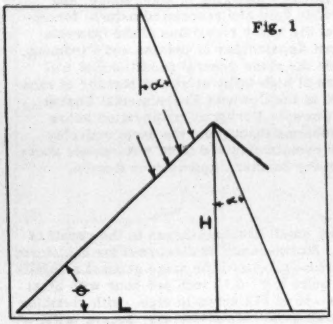

Fig. 1

By extrapolation, the rainfall-rate on Watershed 37 during the high hourly rate shortly preceding peak-flow was about 0.39 inch per hour. The peak-rate of runoff was 167 second-feet per square mile--about 0.26 inch per hour. Thus, detention plus retention was increasing at a rate of about 0.13 inch per hour, or somewhat more as explained above. From the rapid subsequent outflow it appears that this should probably be classed as detention, and had the rates of rainfall that preceded the peaks by about an hour continued for an hour or so more, the resulting peaks would have closely approached the rates of rainfall.

Figure 3 suggests that instead of using elevation as a basis for classification of watersheds, the longitudinal profile might be used to better advantage. Profiles for Watersheds 1, 7, 10, and 14 all tend toward parallelism although their elevations are quite different. Watershed 22, which apparently has no more area above 3,000 feet than Watershed 10, has much steeper slopes, which is an influence in the difference in performance. If one is to use a classification based on elevation, judging from Figure 3 one might say that 3,500 feet would be a better dividing elevation than the 3,000 feet used by the authors.

The authors made no mention of the number of rain-gages from which the average depths of rainfall shown in Table 1 were determined, or anything concerning their exposure. Because of the substantial variation in amount of precipitation, this is important. In a paper presented before the Section of Meteorology on the subject "A comparative study of rain-gages," the authors, H. C. STOREY and E. L. HAMILTON, who are connected with the San Dimas (California) Experiment Station of the Forest Service, raised again the old question of accuracy and significance of records of rainfall in mountainous country. The discussion brought out that a rain-gage with its top parallel to the slope and otherwise satisfactorily exposed would be a measure of the catch on the inclined area. It would appear to the writer that while this may be correct, the vertical angle of the falling rain may theoretically be used with the degree of slope to correct the catch in a rain-gage set with its top in a horizontal plane in order to get the average catch in the horizontal projection of the inclined area (see Fig. 1).

Referring to Figure 1, if rain is falling at an angle α with the vertical, and M is the catch in a rain-gage installed with its top in a horizontal plane, then M′, the corrected value for the catch on the horizontal projection of the slope is $M' = M[(L \pm H \tan \alpha)/L] = M(1 \pm \tan \theta \tan \alpha)$, in which the sign is plus if the slope is exposed, as shown in Figure 1, and negative if sheltered.

If the rain falls in a vertical plane that is perpendicular to the axis of a symmetrical watershed, however, the deficiency of rain below the average on the sheltered side of the watershed tends to be compensated for by excess above the average on the exposed side. But if the rain falls in a vertical plane that tends to parallel the axis of the watershed, the error tends to be greater. Studies should demonstrate whether or not the theoretical correction outlined applies to the usual type of measurements of precipitation in mountainous country, and should be of great help in determining correct quantitative measurements of rainfall on steep slopes and mountain watersheds.

ON THE PLOTTING OF FLOOD-DISCHARGES

E. J. Gumbel

Introduction

We ask: Which frequency shall we attribute to the m'th observation of a statistical variate, and especially to the m'th flood-discharge?

Let $x_m[m = 1, 2, \ldots\ldots (n - 1), n]$ be n observations arranged according to increasing magnitude. The question is, shall we use (m/n) or $[(m - 1)/n]$ as the observed cumulative frequency? Both methods are equally legitimate. The first corresponds to the arrangement of the observations in increasing magnitude, the second to the arrangement in decreasing magnitude.

Our problem has a bearing on the comparison between theory and observation. Let x be a continuous variate, and let $W(x)$ be the probability of a value equal to or less than x. Shall we compare the step-function $[m, x_m]$ or the step-function $[(m - 1), x_m]$ to the theoretical curve $[n\,W(x), x]$. Although both methods are legitimate, we want to compare one and only one observed curve to the theoretical one.

The same problem arises if we deal with the return-periods. For observations recorded in time, the theoretical return-period $T(x)$ of a value equal to or larger than x is defined by

$$T(x) = \left\{1/[1 - W(x)]\right\} \tag{1}$$

There are two ways of plotting the observed return-periods, namely, the so-called exceedance-intervals

$$T'(x) = [n/(n - m)] \tag{2}$$

defined for $1 \leqq m \leqq (n - 1)$, and the recurrence-intervals

$$T''(x_m) = [n/(n - m + 1)] \tag{3}$$

defined for $1 \leqq m \leqq n$. The terminology exceedance- and recurrence-intervals was introduced by HORTON [7]. The exceedance-interval is not defined for the largest observation.

The index m is called the serial number. Small serial numbers and large numbers of observations correspond to small probabilities W. Then the differences between the exceedance- and recurrence-intervals are small. Both approximate

$$T = (1 + W) \tag{4}$$

that is, unity. For large serial numbers, however, especially for the extreme values of the variate, the differences between the two ways of plotting are large. For the penultimate observation $x_{(n - 1)}$ the exceedance-interval is n, and the recurrence-interval is only $(n/2)$. Therefore the question whether to choose (m/n) or $[(m - 1)/n]$ as observed cumulative frequency has practical importance.

ALLEN HAZEN [6] proposed a compromise, a corrected frequency

$$W(x_m) = [(m - 1/2)/n] \tag{5}$$

which has been accepted widely. Hazen's corrected return-periods

$$T(x_m) = [n/(n - m + 1/2)] \tag{5'}$$

may be used for $1 \leqq m \leqq (n - 1)$. For the largest among n observations this method leads to a return-period 2n. But no statistical device can increase the number of observations beyond n. Furthermore, it does not seem safe to attribute a return-period 2n to an event which has already happened within n years. Therefore, Hazen's proposal does not solve the problem.

General solution

In the following we want to decide which compromise (if any) we should make between the recurrence- and exceedance-intervals. We construct a correction Δ for the serial number m, such that the adjusted frequency $\tilde{W}$ and the adjusted return-period $\tilde{T}$ become

$$\tilde{W} = [(m - \Delta)/n] \qquad \tilde{T} = [n/(n - m + \Delta)] \tag{6}$$

The correction Δ, which replaces Hazen's value 1/2, will depend upon the relative serial number (m/n), and upon the theoretical distribution [w(x)], which is adequate for the observations. The correction will be chosen such that a certain probability is a maximum. In this sense the correction Δ is the best one.

If we take a sample of size n from an infinite population submitted to a distribution [w(x)], a certain observation 'a' will be the m'th; its probability is [W(a)]. If we take another sample of the same size, the m'th observation will be different, say 'b'; its probability is [W(b)]. Generally, the m'th among n observations with a distribution [w(x)], is a statistical variate, which has a distribution $[v_n(m, x)]$ depending upon m and n and [w(x)]. The distribution $[v_n(m, x)]$ of the m'th value for an initial distribution w(x) and for n observations is

$$v_n(m, x) = \binom{n}{m} m\, W^{(m-1)}(x)(1 - W(x))^{(n-m)} w(x) \tag{7}$$

It is reasonable to assume that the m'th observation of the array at hand is the most probable value of this distribution. The most probable m'th value, $\tilde{x}_m$, obtained by logarithmic differentiation of equation (7), is the solution of

$$[m - 1 - (n - 1)W(\tilde{x}_m)] = - w'(\tilde{x}_m) w^{-2}(\tilde{x}_m) W(\tilde{x}_m)[1 - W(\tilde{x}_m)] \tag{8}$$

We attribute to the observed m'th value x_m the adjusted frequency

$$\tilde{W} = W(\tilde{x}_m) \tag{9}$$

which is the probability of the most probable m'th value, obtained from equation (8). This probability depends upon the serial number m, the number of observations n, and the initial distribution [w(x)].

Equation (8) may be written in the form

$$(m - n\tilde{W}) = \Delta \tag{10}$$

where the right side

$$\Delta = 1 - \tilde{W} - w'(\tilde{x}_m) w^{-2}(\tilde{x}_m) \tilde{W}(1 - \tilde{W}) \tag{11}$$

henceforth called the correction, depends upon the probability $\tilde{W}$, the initial distribution [w(x)] but not upon n. The adjusted frequency $\tilde{W}$ and the adjusted return-period

$$\tilde{T} = [T(\tilde{x}_m)] \tag{12}$$

of the m'th observation are obtained by introducing equation (11) into equation (6).

For a given distribution, the corrections Δ may be calculated from equation (11) for chosen numerical values of the adjusted frequency $\tilde{W}$. The serial number m as a function of $\tilde{W}$ obtained through equation (6) will not be an integer. The adjusted frequencies $\tilde{W}$ corresponding to integral numbers m are obtained by linear interpolations. If n is large, this tedious work may be avoided. The correction Δ as a function of (m/n) is slightly different from Δ considered as a function of the adjusted frequency $\tilde{W}$. Neglecting this difference, we attribute the calculated value of Δ to (m/n) instead of $\tilde{W}$, and obtain for given values of m the adjusted frequencies $\tilde{W}$ from equation (6). By this procedure, we obtain the adjusted frequency and the adjusted return-period for any number of observations, any serial number, and any initial distribution. The adjusted return-periods allow the plotting of the first and the last observation, whereas the last observation has to be omitted if we plot the exceedance-intervals.

The calculation of the corrections may be simplified for symmetrical distributions, if we introduce a reduced variate z defined by

$$z = [(x - \bar{x})/\sigma] \tag{13}$$

where x stands for the arithmetic mean and σ for the standard deviation. The probabilities $[W(-z)]$ and $[W(z)]$ are then related by

$$W(-z) + W(z) = 1 \tag{14}$$

The same symmetry holds for the correction $[\Delta(z)]$ and $[\Delta(-z)]$. For we obtain in this case from equation (11)

$$[\Delta(-z)] + [\Delta(z)] = 1 \tag{15}$$

The adjusted frequency of the arithmetic mean of a symmetrical distribution is Hazen's value (5).

For an exponential distribution $w(x) = a\,\mathrm{Exp}(-ax)$ the adjusted frequency of the m'th observation obtained from equation (10) and (11) is

$$\tilde{W} = [(m - 1)/n] \tag{16}$$

and the adjusted return-periods are the recurrence-intervals, equation (3). For the uniform distribution, where $[w'(x)] = 0$, we obtain

$$\tilde{W} = [(m - 1)/(n - 1)] \tag{17}$$

Although the corrections vary for different distributions, they have some common properties, provided the number of observations is large and the variates are unlimited. For small serial numbers--that is, for the first observations--the probability W and the density of probability $[w(x)]$ approach zero. If the quotient $[W(x)/w(x)]$ becomes indeterminate, and if the distribution is such that HOPITAL's rule holds, we may write

$$\lim_{x = -\infty} [W(x)\,w'(x)/w^2(x)] = 1 \tag{18}$$

The correction Δ in equation (11) converges towards zero. For large serial numbers--that is, for the last observations--the probability $[1 - W(x)]$ and the density of probability $[w(x)]$ approach zero. If the quotient $\{[1 - W(x)]/w(x)\}$ becomes indeterminate, and if the distribution is such that Hopital's rule holds, we may write

$$\lim_{x = \infty} \{[1 - W(x)\,w'(x)]/w^2(x)\} = -1 \tag{19}$$

The negative sign enters as the density of probability $[w(x)]$ diminishes for increasing values of x. The correction Δ in equation (11) converges towards unity. If the conditions of equations (18) and (19) hold, the correction Δ is limited by

$$\lim_{n = +\infty} \Delta(x_1) = 0 \qquad \lim_{n = \infty} \Delta(x_n) = 1 \tag{20}$$

The adjusted frequency of the smallest observation converges for an increasing number of observations towards

$$\tilde{W} = (m/n) \tag{21}$$

and the adjusted return-periods converge towards the exceedance-intervals. The adjusted frequency of the largest observation converges towards

$$\tilde{W} = [(m - 1)/n] \tag{21'}$$

and the adjusted return-periods converge towards the recurrence-intervals. The numbers of observations necessary for the use of these asymptotic values vary for different distributions.

From equations (21) and (21') follows a relation of symmetry. If we replace the serial number m by (n - m + 1), the adjusted return-period of the $(n - m + 1)^{st}$ observation (which is the m'th in decreasing magnitude)

$$T[\tilde{x}_{(n-m+1)}] = (n/m) = [1/W(\tilde{x}_m)] \qquad (21'')$$

is equal to the reciprocal of the adjusted frequency of the m'th observation. For asymmetrical distributions, this holds only provided that the number of observations is sufficiently large. For symmetrical distributions this relation follows from equations (14), (15), and (6), and holds for any number of observations.

If the conditions of equations (18) and (19) are fulfilled, and if the number of observations is sufficiently large, the adjusted return-periods $\tilde{T}$--equation (6)--start with the exceedance-intervals. For increasing serial numbers the adjusted return-periods become smaller than the exceedance-intervals and reach the recurrence-intervals for the last observations.

This property may be used to construct approximations $\overline{W}$ and $\overline{T}$ for the adjusted values $\tilde{W}$ and and $\tilde{T}$. In many practical cases, the initial distribution is unknown. Then the problem of how to choose the correction does not have an exact solution. In this case we speak of corrected or approximate frequencies and return-periods. To obtain approximate values, we assume n to be large and the variate to be limited and subject to the conditions of equations (18) and (19). The corrected frequencies of the first and last observations are then

$$\overline{W}(x_1) = (1/n) \qquad \overline{W}(x_n) = (1 - 1/n)$$

or at least near to these values. These two conditions seem to be incompatible as there are n and not (n - 1) steps between the first and the last observation. To reconcile them we set

$$\overline{W}(x_m) = (m/n) - [(m - 1)/n(n - 1)] \qquad (22)$$

This gives n steps of length $[1/(n - 1)]$ instead of $[1/n]$. The approximate frequencies $\overline{W}$ are given in Table 2 [columns (4), (7), and (10) for 5, 10, and 20 observations]. The general correction

$$\bar{\Delta} = [(m - 1)/(n - 1)] \qquad (23)$$

is smaller (equal to, or larger than) Hazen's correction if $m \lesseqgtr [(n + 1)/2]$. The general correction $\bar{\Delta}(x_m)$ for the m'th observation is related to the general correction $\bar{\Delta}[x_{(n-m+1)}]$ of the $(n - m + 1)^{st}$ observation by

$$\bar{\Delta}(x_m) + \bar{\Delta}[x_{(n-m+1)}] = 1$$

This is the relation of equation (15), which holds for symmetrical distributions. Therefore, equation (23) cannot be used if there are reasons to assume that the initial distribution is decidedly skew. The approximate return-period, for which we write T, is

$$\overline{T} = \left\{n/[n - m + (m - 1)/(n - 1)]\right\} \qquad (24)$$

This value shares the properties of the adjusted value $\tilde{T}$. It passes between the exceedance- and recurrence-intervals. Equation (21'') remains valid. If the distribution is unknown, the return-period, equation (24), should be used instead of Hazen's value of equation (5').

Hazen's return-periods $T(x_m)$, the adjusted return-periods $[\tilde{T}(x_m)]$, and the approximations $[\overline{T}(x_m)]$ are weighted harmonic means of the recurrence-intervals $[T''(x_m)]$ and the exceedance-intervals $[T'(x_m)]$ with positive weights a and (1 - a), respectively. In Hazen's case we have $a = 1/2$, a relation which has been found by B. F. KIMBALL [9]. For the adjusted return-periods $\tilde{T}$ and the approximation $\overline{T}$ the weights a are Δ and $[(m - 1)/(n - 1)]$, respectively.

Another general approximation is

$$\overline{W}'(x_m) = [m/(n + 1)] \qquad \overline{T}'(x_m) = [(n + 1)/(n - m + 1)] \qquad (24')$$

Here we have n steps of length $1/(n + 1)$. The equations (15) and (21'') hold. For large n the numerical differences between equations (24') and (22) are very small. However, the relation of the ad-

Table 1--Corrections Δ and Δ^* for the normal distribution and the distribution of the largest value

Adjusted frequency, Φ, Φ^* (1)	Normal Δ (2)	Largest value Δ^* (3)	Adjusted frequency, Φ, Φ^* (1)	Normal Δ (2)	Largest value Δ^* (3)
.010	.1258	.2150	.55	.5286	.7527
.015	.1383	.2345	.60	.5573	.7830
.020	.1493	.2505	.65	.5867	.8125
.025	.1597	.2643	.70	.6167	.8411
.03	.1654	.2766	.75	.6479	.8690
.04	.1797	.2982	.80	.6810	.8962
.05	.1923	.3171	.85	.7168	.9230
.06	.2038	.3341	.90	.7572	.9491
.07	.2144	.3497	.91	.7664	.9543
.08	.2243	.3643	.92	.7757	.9594
.09	.2336	.3779	.93	.7856	.9646
.10	.2408	.3909	.94	.7962	.9700
.15	.2832	.4481	.95	.8077	.9748
.20	.3190	.4971	.96	.8203	.9799
.25	.3521	.5410	.97	.8346	.9849
.30	.3833	.5814	.975	.8403	.9874
.35	.4133	.6192	.980	.8507	.9900
.40	.4427	.6548	.985	.8617	.9925
.45	.4714	.6888	.990	.8742	.9950
.50	.5000	.7214			

Table 2--Adjusted frequencies for 5, 10, and 20 observations

Serial No., m	n = 5			n = 10			n = 20		
	Normal	Largest	Approx.	Normal	Largest	Approx.	Normal	Largest	Approx.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
1	.144	.118	.20	.078	.066	.100	.041	.036	.050
2	.321	.286	.35	.170	.155	.189	.089	.082	.097
3	.500	.461	.50	.264	.246	.278	.136	.129	.145
4	.679	.639	.65	.358	.339	.367	.185	.176	.192
5	.856	.819	.80	.453	.432	.456	.232	.224	.239
6	.....	.....	....	.547	.526	.544	.281	.272	.287
7	.....	.....	....	.642	.620	.633	.330	.320	.334
8	.....	.....	....	.736	.715	.722	.379	.368	.382
9	.....	.....	....	.830	.810	.811	.427	.417	.429
10	.....	.....	....	.922	.905	.900	.475	.465	.476
11	.....	.....	....	.....	.....	.....	.525	.514	.524
12	.....	.....	....	.....	.....	.....	.573	.562	.571
13	.....	.....	....	.....	.....	.....	.621	.610	.618
14	.....	.....	....	.....	.....	.....	.670	.659	.666
15	.....	.....	....	.....	.....	.....	.719	.708	.713
16	.....	.....	....	.....	.....	.....	.768	.756	.761
17	.....	.....	....	.....	.....	.....	.815	.805	.808
18	.....	.....	....	.....	.....	.....	.864	.854	.855
19	.....	.....	....	.....	.....	.....	.911	.903	.903
20	.....	.....	....	.....	.....	.....	.959	.951	.950

justed return-periods, equation (24), to the exceedance- and recurrence-intervals is simpler than the corresponding relation for equation (24').

Normal values and the flood-flow

In the following we calculate the corrections for two distributions which play an important role in hydrology, namely, the normal distribution and the distribution of the largest value.

The adjusted frequency of the last observation taken from a normal distribution has already been calculated by R. W. BLYTHE [1]. The solution for any serial number is obtained if we introduce into equation (10) the normal distribution

$$w(x) = [e^{-z^2}/(\sigma\sqrt{2\pi})] \tag{25}$$

where z is related to x by equation (13). If we omit the variate x_m, equation (11) becomes

$$\Delta = [1 - \tilde{W} + 2z\tilde{w}^{-1}\tilde{W}(1 - \tilde{W})] \tag{26}$$

where $\tilde{w} = w(\tilde{x}_m)$.

The numerical values of the correction of equation (26) are shown in Table 1. The first column gives the adjusted frequency $\tilde{W}$. The second column obtained from tables of the probability-function [11] gives the correction Δ. For a given number of observations we multiply the first column by n, add it to the second column, and obtain the serial number m as a function of $\tilde{W}$. Then we know the adjusted frequency $\tilde{W}$, which has to be attributed to the observation x_m.

Table 2 gives, in columns (2), (5), and (8), the adjusted frequencies for 5, 10, and 20 observations taken from a normal distribution. Due to the symmetry of this distribution, the adjusted frequencies $[W(\tilde{x}_m)]$ are equal to the adjusted frequencies $W[\tilde{x}_{(n-m+1)}]$. The differences between the adjusted normal frequencies and the approximations of equation (22)--given in columns (4), (7), (10)--converge rapidly towards zero for increasing number of observations.

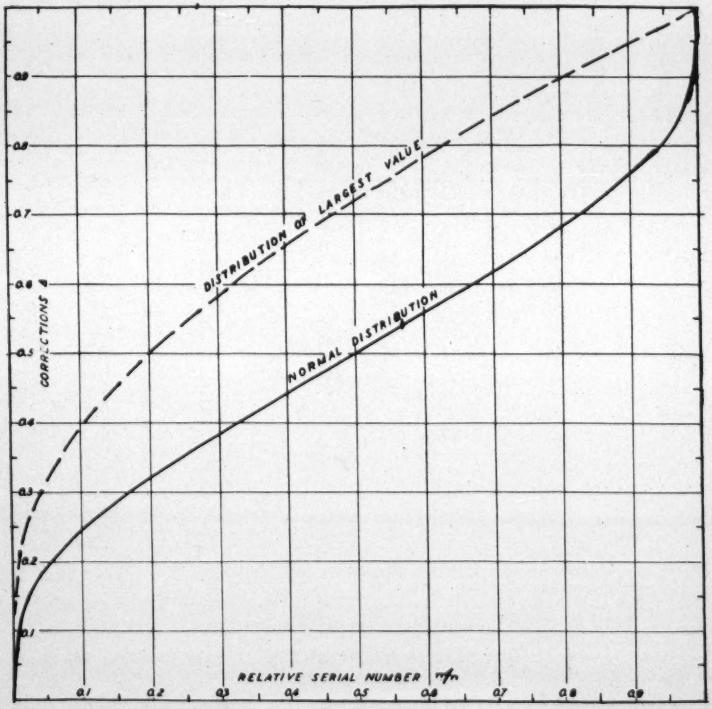

Fig. 1--Corrections

To obtain the adjusted normal frequencies for any number of observations, we plot in Figure 1 the correction Δ, taken from Table 1 and equation (20), and write on the abscissa (m/n) instead of $\bar{W}$. The adjusted frequencies $\bar{W}$ are then obtained from equation (6). The problem of how to plot observations, which follow the normal law, is thus settled.

We may interpret the abscissa in Figure 1 as being the exceedance-interval, its upper parallel as the recurrence-interval; then the curve $[\Delta, (m/n)]$ shows how the adjusted return-periods pass for increasing serial numbers from the exceedance-intervals to the recurrence-intervals.

The differences $[(m/n) - \bar{W}]$ between the observed frequency (m/n) and the corrected frequency $\bar{W}$ are plotted in Figure 2 for different distributions and for ten observations. The curves pertaining to the normal distribution and the general approximation are taken from Table 2. The two straight lines for the uniform and exponential distributions are obtained from equations (16) and (17). Figure 2 shows that for small numbers of observations the correction depends strongly upon the distribution.

The corrections are important if we consider the return-periods of the flood-discharges. The theoretical distribution, which corresponds to the flood-discharges, is found by the theory of the largest value [2]. The probability W^* that a largest value is equal to or less than x is

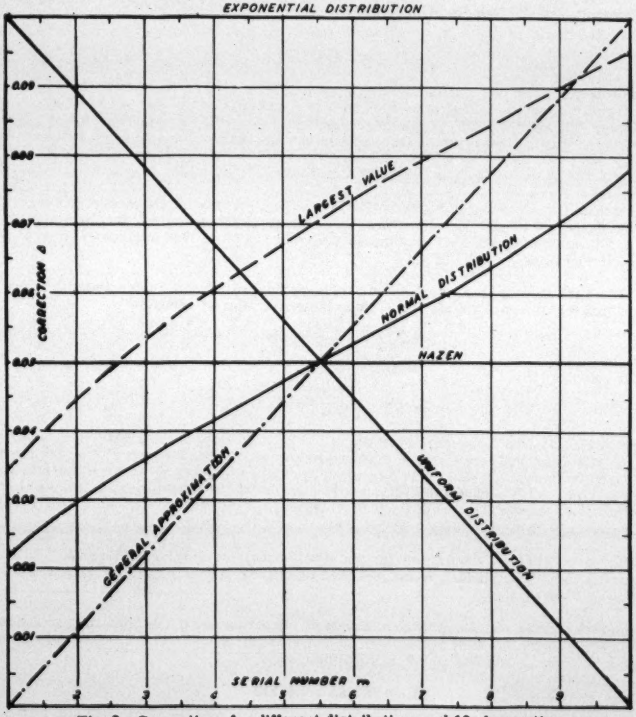

Fig. 2--Corrections for different distributions and 10 observations

$$W^* = \text{Exp}\,[-\,\text{Exp}\,(-y)] \tag{27}$$

where the reduced, dimensionless, variate y is

$$y = \alpha(x - u) \tag{28}$$

The two parameters u and $(1/\alpha)$ have the dimension x. Their determination will be explained later.

For the normal curve the probability of a value below three times the standard deviation is 0.99865, whereas W* reaches this value only for five times the standard deviation. The distribution $w^*(x)$ of the largest value is

$$w^*(x) = \alpha\,\text{Exp}\,[-\,y - \text{Exp}\,(-\,y)] \tag{29}$$

This density of probability is maximum for y = 0--that is, x = u. The parameter u, the most probable annual flood, may be estimated [4] from the observed flood-discharges through the relation

$$u = \bar{u} - 0.58721\,\theta \tag{30}$$

where u stands for the mean annual flood. The value θ called mean deviation, is the mean of the absolute deviations calculated from the mean annual flood. The other parameter has been shown [4] to be

$$(1/\alpha) = 1.01731\,\theta \tag{31}$$

Another interpretation of $(1/\alpha)$ is obtained if we introduce the return-period. As we deal with flood-discharges, the return-period is counted in years, and [W(x)] is replaced by $[W^*(x)]$. Combining equations (27) and (28) with (1), we obtain [see reference (2)] the return-period of a flood equal to or larger than x converges for large values of x towards

$$\ln T(x) = \alpha(x - u) \tag{32}$$

The flood-discharge x occurring in equation (32) is the most probable flood-discharge corresponding to the return-period [T(x)]. For observations in excess of 20 years, the most probable flood-discharge is a linear function of the logarithm of the return-period. The parameter $(1/\alpha)$ is the slope of this straight line.

To establish the adjusted frequencies and return-periods of the flood-discharges we substitute equation (27) into the general formula (11). Then, the correction Δ^* becomes

$$\Delta^* = -\,[(1 - \tilde{W}^*)/\ln \tilde{W}^*] \tag{33}$$

whence from equation (10)

$$(m - n\,\tilde{W}^*) = -\,[(1 - \tilde{W}^*)/\ln \tilde{W}^*] \tag{34}$$

This gives the adjusted frequency $\tilde{W}^*$ of the m'th observed flood for any number of observations. The first column in Table 1 is now interpreted as the adjusted frequency $\tilde{W}^*$. The third column obtained from equation (33) gives the corrections Δ^*, which are plotted in Figure 1. Table 2--columns (3), (6), and (9)--shows the adjusted frequencies of the flood-discharges for 5, 10, and 20 observations. As the distribution of flood-discharges is asymmetrical, the adjusted frequencies $[W^*(\tilde{x}_m)]$ are smaller than the adjusted frequencies $1 - W^*\,[\tilde{x}_{(n-m+1)}]$.

The differences $[(m/n) - \tilde{W}^*]$ arising for ten observations are plotted in Figure 2. The adjusted return-periods of the flood-flow are obtained by introducing the numerical values of the correction Δ^* into equation (6).

Equation (34) may be used for a quick estimate of the parameter u. According to equation (27) the probability $[W^*(u)]$ of the most probable annual flood is $[W^*(u)] = (1/e)$. The most probable serial number $\tilde{m}$ of the mode obtained from equation (34) is

$$\tilde{m} = 0.36788n - 0.63212 \tag{35}$$

Finally, the mode u is obtained by linear interpolation between the observed flood-discharges x_m and $x_{(m+1)}$, where $(m - 1) \leq \tilde{m} \leq m$. This estimate of the mode is preferable to the more complicated method proposed in a previous paper [4].

Extremes

In principle, the corrections for the frequencies and the return-periods are given by equations (10) and (11), once the initial distribution is known. It is interesting to consider specially the extreme observations, namely, the first, second, third, and the last, penultimate, and the preceding values. For large numbers of observations, the adjusted frequencies are obtained from equations (21) and (21'). The question is, which adjusted frequencies result from our theory for a small number of observations?

In the following, we calculate the adjusted frequencies of the first and the last observation. Then we establish a recurrence-method, which leads from the adjusted frequency of the m'th observation to the adjusted frequencies of the $(m - 1)^{st}$ observation.

The adjusted frequency $\widetilde{W} = [W(\widetilde{x})]$ of the first observation obtained from equation (10) by setting m = 1, may be written

$$n = [(1 - \Delta)/\widetilde{W}] \tag{36}$$

For a given initial distribution, we choose numerical values for $(1/\widetilde{W})$ and obtain Δ from equation (11) and n from equation (36). This is the number of observations, such that $\widetilde{W}$ is the adjusted frequency of the first among n observations.

For the second among n_2 observations we obtain from equation (10), by setting m = 2, $n_2 = [(2 - \Delta)/\widetilde{W}]$. If we choose for $\widetilde{W}$ the same numerical values as before, this equation becomes

$$n_2 = [n + (1/\widetilde{W})] \tag{37}$$

where $\widetilde{W}$ is now the adjusted frequency for the second among n_2 observations. In the same way,

$$n_3 = [n_2 + (1/\widetilde{W})] \qquad n_4 = [n_3 + (1/\widetilde{W})] \qquad n_5 = [n_4 + (1/\widetilde{W})] \tag{37'}$$

where n_3, n_4, and n_5 stand for the number of observations such that $\widetilde{W}$ is the adjusted frequency of the 3rd, 4th, 5th observation. To obtain the adjusted frequencies of the smallest observations it is only necessary to calculate n from equation (36). The other values are then obtained by simple addition. As $(1/\widetilde{W})$ is of the order n, the graphic representation of the relations of equations (36), (37), and (37') consist in plotting on a double logarithmic scale $(1/\widetilde{W})$ on the ordinate, and the number of observations on the abscissa. If the initial distribution is symmetrical, the adjusted frequencies of the last observations are obtained from the adjusted frequencies of the first observations through the relation of equation (14). This means that $(1/\widetilde{W})$ is replaced by the adjusted return-period $\widetilde{T}$.

A separate consideration of the last observations is necessary if the initial distribution is asymmetrical. The frequencies of the last, penultimate, and the preceding observations are near to unity. A small increase, say (p/100), in the frequency chosen for plotting these observations implies a large increase $[T^2p/(100 - Tp)]$ in the corresponding return-period. Therefore, we consider the return-periods instead of the frequencies. For a chosen initial distribution w(x) the adjusted frequency $\widetilde{W}$ of the last among n observations, obtained from equation (10) by putting m = n, is

$$n = [\Delta/(1 - \widetilde{W})] \tag{38}$$

We choose numerical values of $\widetilde{W}$, calculate Δ, and obtain the corresponding number of observations n. The adjusted return-period is then $\widetilde{T} = [1/(1 - \widetilde{W})]$. For the penultimate among n_2 observations, we put in equation (10) $m = (n_2 - 1)$, and replace the n by n_2. The number n_2 of observations, such that $\widetilde{T}$ is the adjusted return-period of the penultimate observation, is

$$n_2 = [(1 + \Delta)/(1 - \widetilde{W})] \tag{39}$$

In the same way, we obtain

$$n_3 = (n_2 + \widetilde{T}) \qquad n_4 = (n_3 + \widetilde{T}) \qquad n_5 = (n_4 + \widetilde{T}) \tag{39'}$$

where n_3, n_4, and n_5 stand for the number of observations such that $\widetilde{T}$ is the adjusted return-period of the third, fourth, and fifth observation, arranged in decreasing magnitude. As n is of the order

Table 3--Adjusted normal frequencies for the first five observations

Reduced variable, z	Adjusted		Number of observations				
	Frequency, $\tilde{W}$	Return period, $\tilde{T}$	m = n	m = (n - 1) n_2	m = (n - 2) n_3	m = (n - 3) n_4	m = (n - 4) n_5
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
0.00	.50000	2.000	1.000	3.000	5.000	7.000	9.000
0.25	.63816	2.764	1.602	4.366	7.129	9.893	12.66
0.50	.76025	4.171	2.730	6.901	11.072	15.24	19.41
0.75	.85558	6.924	4.992	11.92	18.84	25.76	32.69
1.00	.92135	12.72	9.878	22.59	35.31	48.02	60.74
1.25	.96145	25.94	21.33	47.27	73.21	99.15	125.1
1.50	.98305	59.00	50.59	109.6	168.6	227.6	286.6
1.75	.99334	150.1	132.8	282.8	432.9	582.9	733.0
2.00	.99766	427.6	387.2	814.7	1242	1670	2097
2.25	.99927	1267	1260	2627	3995	5362	6729

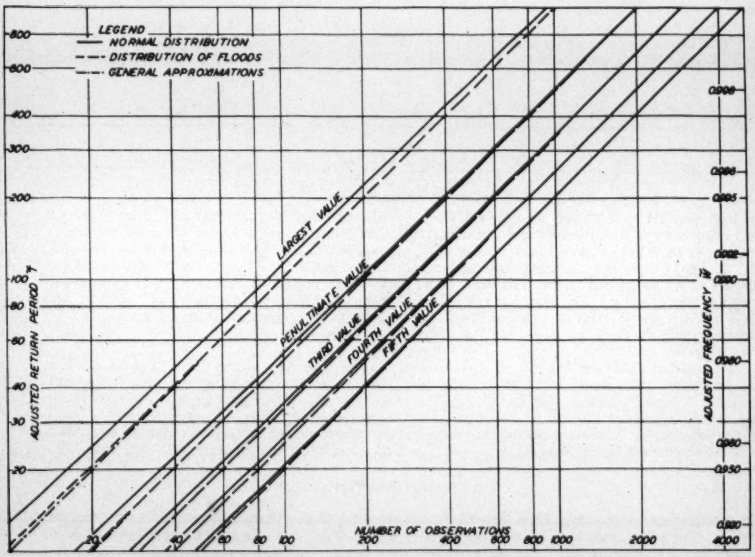

Fig. 3--Adjusted frequencies and return-periods for extreme observations

$\tilde{T}$, the graphic representation of the relations of equations (38), (39), and (39′) consists in plotting, on a double logarithm scale, the return-periods $\tilde{T}$ as a function of the number of observations n.

We apply this procedure to the normal distribution and to the distribution of the largest value. For the normal distribution we obtain the number of observations n from the adjusted frequency W of the last observation by introducing equation (26) into equation (38), whence

$$n = 1 + 2z\,\tilde{W}\,\tilde{w}^{-1} \qquad (40)$$

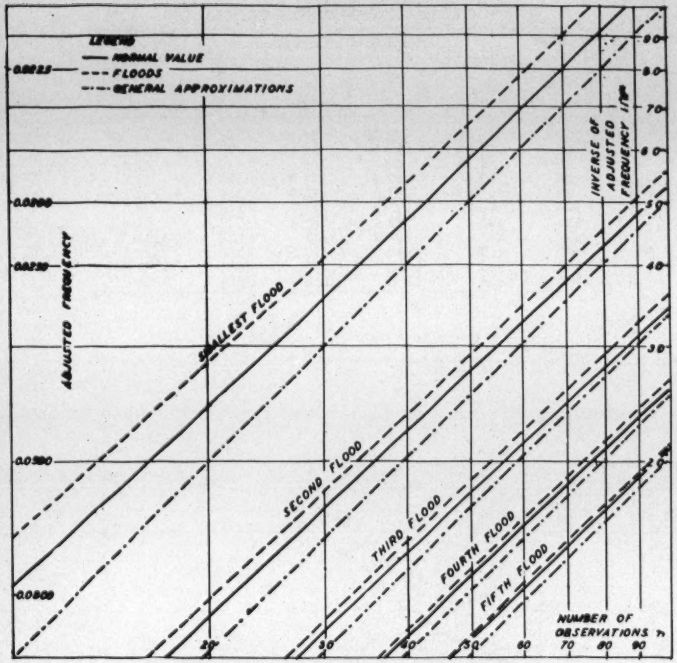

Fig. 4--Adjusted frequencies for smallest observations

Table 3 gives the adjusted frequency W in column (2) and the adjusted return-period $\widetilde{T}$ in column (3) as a function of the reduced variate z in column (1). The succeeding columns, obtained from equations (40), (39), and (39'), give the number of observations n, n_2, n_3, n_4, and n_5, such that $\widetilde{W}$ and $\widetilde{T}$ are the adjusted frequencies and return-periods for the last, penultimate, and the preceding observations. As the normal distribution is symmetrical, the adjusted frequencies of the first five observations are equal to $(1 - \widetilde{W})$. In this case, the variate takes on the values - z.

The adjusted probability $[W(\widetilde{z}_n)]$ of the last observation and the corresponding reduced variate z listed in Table 3 in columns (1) and (2), differ slightly from the values given by R. W. BLYTHE [1]. This is due to the fact that Blythe calculated the most probable largest value through an approximate formula.

The adjusted frequencies and return-periods for the first and last five normal observations are plotted in Figure 3 on double logarithmic scale. On the abscissa we write the number of observations. On the left (respectively right) scale of the ordinate we write the adjusted return-periods (respective frequencies). Figure 3 shows how the adjusted return-periods of the largest (smallest) observations converge towards the exceedance- (recurrence-) intervals, as stated in equations (21) and (21'). However, these results hold only for numbers of observation which exceed by far the length of the records that we usually have for consideration.

In the following we apply the methods developed above to the distribution of the flood-discharges. For the smallest flood, m = 1, we obtain from equations (36) and (33)

Table 4--Adjusted frequencies for first five floods

Inverse of adjusted frequency, $(1/\tilde{W}^*)$ (1)	Number of observations m = 1 n (2)	2 n_2 (3)	3 n_3 (4)	4 n_4 (5)	5 n_5 (6)
10	6.091	16.09	26.09	36.09	46.09
20	13.66	33.66	53.66	73.66	93.66
40	29.43	69.43	109.4	149.4	189.4
50	37.47	87.47	137.5	187.5	237.5
80	61.97	142.0	222.0	302.0	382.0
100	78.50	178.5	278.5	378.5	478.5
200	162.4	362.4	562.4	762.4	962.4
400	333.4	733.4	1133	1533	1933
500	419.7	919.7	1420	1920	2420
800	680.5	1481	2281	3081	3881
1000	855.4	1855	2855	3855	4855

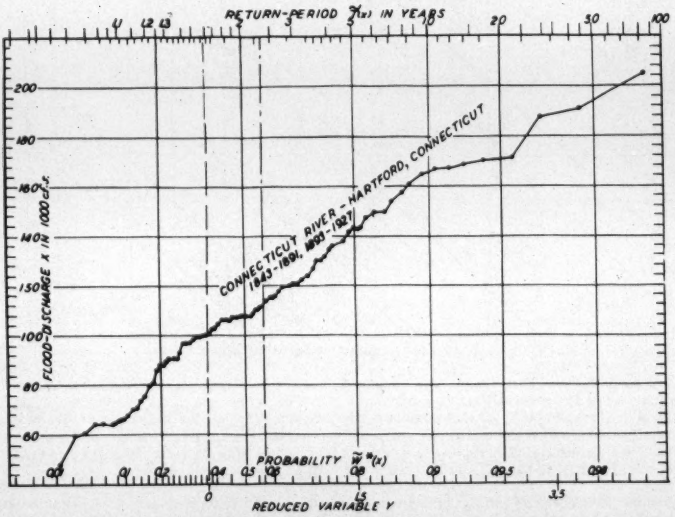

Fig. 5--Adjusted return-periods, Connecticut River, Hartford 1843-1891 and 1893-1927

$$n = (1/\tilde{W}^*) + 1/(\tilde{W}^* \ln \tilde{W}^*) - (1/\ln \tilde{W}^*) \qquad (41)$$

Clearly the product $n\tilde{W}$ converges towards unity, as indicated by formula (20). But this fact does not allow the calculation of the adjusted frequency. We choose [Table 4, column (1)] numerical values for $\tilde{W}$, and calculate from equation (41) the corresponding number of observations n. [Table 4, column (2)]. The numbers n_2, n_3, n_4, and n_5 [Table 4, columns (3) to (6)], such that $\tilde{W}$ is is the adjusted frequency of the second, third, fourth, and fifth flood-discharge, are obtained from equations (39) and (39'). Figure 4 shows the adjusted frequencies $\tilde{W}^*$ for the first five flood-discharges, the first five normal observations, and the approximate value of equation (22) as a function of the numbers of observation n. The adjusted frequencies for the normal values are situated between the adjusted flood-discharges and the general approximation. For increasing values of n the differences between the three curves diminish. The same holds for increasing serial numbers.

We consider now the adjusted frequency $[\tilde{W}^*(x_n)]$ of the largest flood. From equations (38) and (33) we obtain

$$[W^*(\tilde{x}_n)] = \text{Exp}\,[-(1/n)] \tag{42}$$

The adjusted return-period converges quickly towards

$$[T(\tilde{x}_n)] = (n + 1/2) \tag{43}$$

If n is large compared to 1/2, the adjusted return-period of the largest flood is the recurrence-interval. The curve of the adjusted return-period $\tilde{T}$ versus the number of observation n is a straight line if plotted on a double logarithmic scale (Fig. 3). From equations (43) and (32) we conclude

$$\ln (n + 1/2) = \alpha (x - u) \tag{44}$$

where x stands for the most probable flood-discharge to be expected within n years. If the number

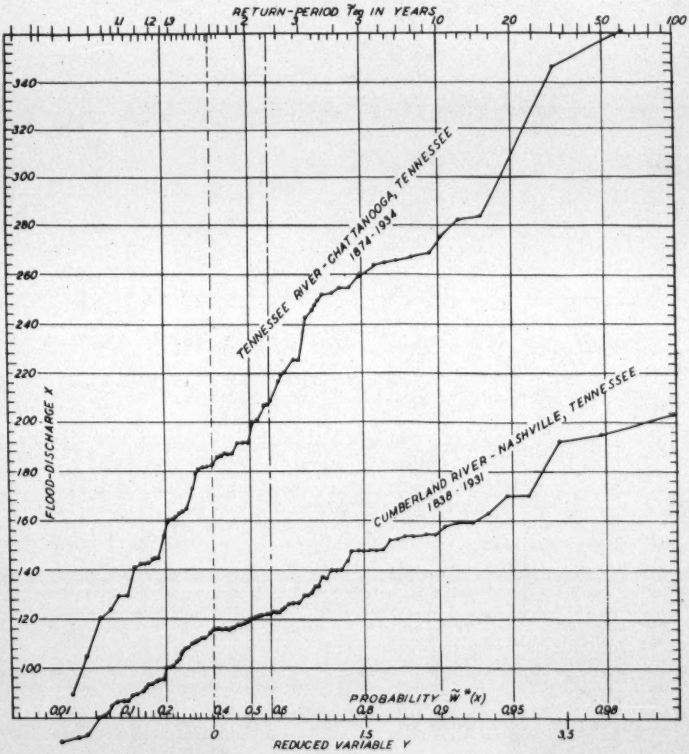

Fig. 6--Adjusted return-periods, Tennessee River, Chattanooga 1874-1934, and Cumberland River, Nashville 1838-1931

of years under observation is multiplied by e, the most probable flood increases by $(1/\alpha)$. If the number of years under observation is doubled, the most probable flood is increased by $(0.69315/\alpha)$.

From the adjusted return-periods of the last flood-discharge as a function of the number of observations we obtain from equations (39) and (39') the adjusted return-periods of the penultimate and the preceding floods. The adjusted return-periods and frequencies for the last five floods are plotted in Figure 3. The adjusted frequencies of the largest flood-discharges are smaller than the adjusted normal frequencies because the normal probability converges more rapidly towards unity than the probability of the flood-discharges. On the other hand, the adjusted frequencies of the flood-discharges are practically identical with the adjusted frequencies obtained from the general formula (22). These approximations may, therefore, safely be used instead of the adjusted values except for the smallest flood-discharges (Fig. 4). As the return-periods of these discharges do not present any particular interest, we may always use the approximations of equations (22) and (24) provided the number of observations is large, say, at least 50.

To obtain an analytic expression for the adjusted return-periods of the extreme floods, we assume n to be large and m = n, (n - 1), (n - 2), (n - 3), and (n - 4). For these extreme floods we put

$$\tilde{W}^* = \text{Exp}\,(-\epsilon) \qquad \tilde{T} = (1/\epsilon)$$

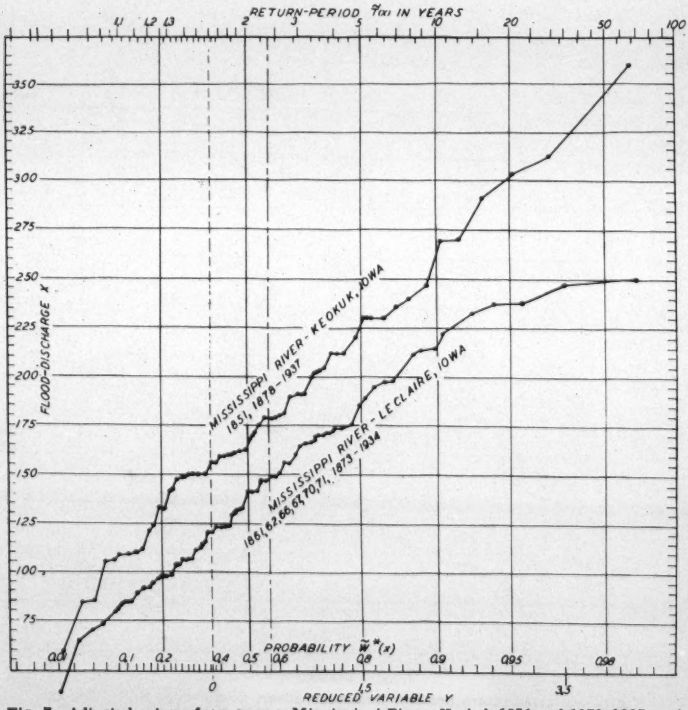

Fig. 7--Adjusted return-frequencies, Mississippi River, Keokuk 1851 and 1878-1937, and Le Claire 1861, 1862, 1866, 1867, 1870, 1871, 1873-1934

and obtain from equation (34) by expansion of the exponential function the adjusted return-period of the m'th flood

$$\tilde{T} = (n + 1/2)/(n - m + 1) \qquad (45)$$

a formula which is similar to (24'). The adjusted frequencies of the largest flood become

$$W^*(\tilde{x}_m) = (m - 1/2)/(n + 1/2) \qquad (46)$$

where m is counted on an ascending scale. The adjusted return-periods of the largest discharges are

$$T[\tilde{x}_{(n-1)}] = (n/2) + (1/4) \qquad T[\tilde{x}_{(n-2)}] = (n/3) + (1/6) \qquad T[\tilde{x}_{(n-3)}] = (n/4) + (1/8) \qquad (47)$$

If the number of observations is large compared to 1/2, there is no compromise required between the recurrence- and exceedance-intervals. For the largest floods we have to plot the recurrence-intervals. It takes (n/m) years for the m'th flood to happen (m is counted downwards).

From equations (43) and (45) follows a relation of symmetry: The largest flood observed for n years has the same adjusted return-period and frequency as the m'th flood (m counted downwards) for m × n years. The most probable largest flood for n years is the most probable m'th flood for m × n years. Generally, the most probable m'th flood for m × n years is the most

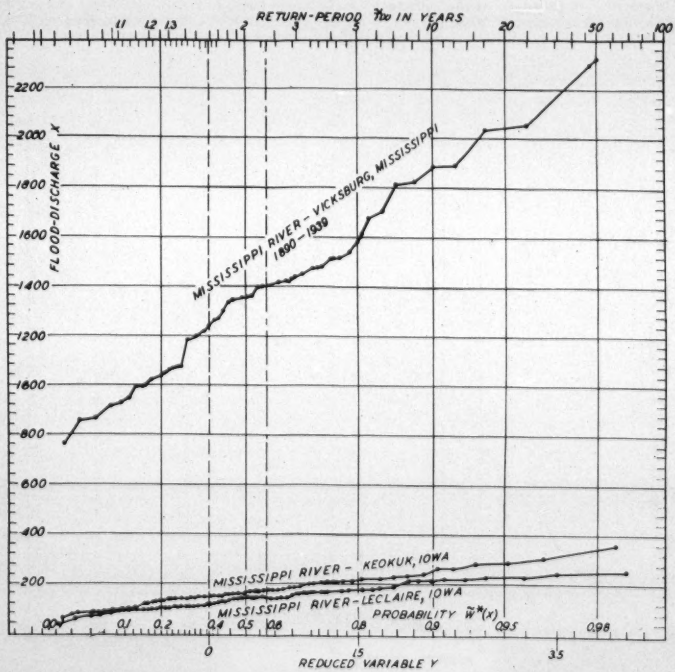

Fig. 8--Adjusted return-periods, Mississippi River, Vicksburg 1890-1939, and Keokuk and Le Claire

probable (m + k')th flood for (m + k) n years, where k = 1, 2, ..., a result which meets with common sense.

Examples

We apply the methods developed before to the flood-discharges of the Connecticut River, Hartford (Connecticut) during 1843-91 and 1893-1927, the Tennessee River at Chattanooga (Tennessee) during 1874-1934, the Cumberland River at Nashville (Tennessee) during 1838-1931, the Mississippi River at Le Claire (Iowa) for 68 years, at Keokuk (Iowa) during 1851 and 1878-1937, and at Vicksburg (Mississippi) during 1890-1930, the Columbia River at The Dallas (Oregon) during 1858-1940, the Rhine at Basel (Switzerland) during 1808-1933, the Rhône at Lyon (France) during 1826-1936, and to the largest monthly precipitation at Boston from 1818-1940. The observations are given in previous papers [2 to 5]. For numbers of observations of the order 50 or less, the adjusted frequencies $\tilde{W}$ are obtained from Table 1. For large numbers of observations the approximate values $\tilde{W}$ obtained from equation (22) were sufficiently exact.

For plotting we use the probability-paper described by R. W POWELL [8,10]. The flood-discharges x_m are the ordinates. The abscissa contains the reduced variate y, but instead of y we write on the lower scale the frequencies W, and on the upper scale the return-periods T given by equation (1). This paper is constructed in the same way as the normal probability-paper, and shares all its properties. The probabilities zero and unity do not appear. Therefore, the recurrence-interval for the smallest observation cannot be plotted. Instead of the recurrence- and exceedance-intervals $\underline{T}'$ and T'', we plot for $n \leq 50$ the adjusted return-period $\tilde{T}$ and for $n > 50$ the approximations T. According to equation (32), we ought to obtain a straight line for the return-periods plotted against the discharges. Indeed, the observations plotted in Figures 5, 6, 7, 8, 9, 10, and 11 are scattered around straight lines. This confirms our theory and our methods.

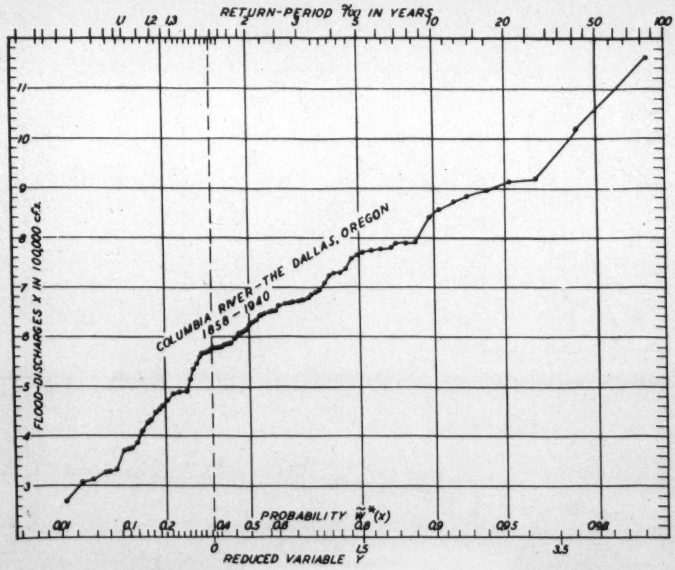

Fig. 9--Adjusted return-periods, Columbia River, The Dalles 1858-1940

Conclusion

There are two ways of plotting the observed cumulative frequencies, and two ways of plotting the observed return-periods. Both ways are justified. However, it is a logical postulate to compare one and only one observed series with the theoretical series. Therefore, we attribute to the m'th observation x_m an adjusted cumulative frequency $[W(\tilde{x}_m)]$, which is the probability of the most probable m'th value, obtained from equations (10) and (11). To facilitate this procedure, we give tables of the difference $[(m/n) - \tilde{W}]$ for the normal distribution and the distribution of the largest value. If the theoretical distribution of the observed sample is unknown, the problem of the correction has no exact solution. However, under certain analytical conditions, which are not very restrictive, we obtain an approximate solution by equation (22). For large numbers of observation, the approximate solution may be substituted for the adjusted frequencies.

For the flood-discharges, the smallest observations are of no peculiar interest; therefore, the approximate frequencies may safely be used if the number of observations is larger than 50. The adjusted return-periods of the largest flood-discharges are the recurrence-intervals. For the plotting of the flood-discharges and largest rains, we use the probability-paper constructed for the theory of the largest value. The fit is very satisfactory.

If the variate possesses a single mode, the correction Δ in equation (11) is smaller than unity (or positive) before (or after) the mode. Consequently the adjusted return-periods (12) surpass the recurrence-intervals before the mode and fall short of the exceedance-intervals after the mode. From this result and the asymptotic equations (21), (21') follows: If an unlimited variate possesses a mode and only one mode, the adjusted return-periods pass, for large numbers of observations and for increasing values of the variate, from the exceedance-intervals to the recurrence-intervals.

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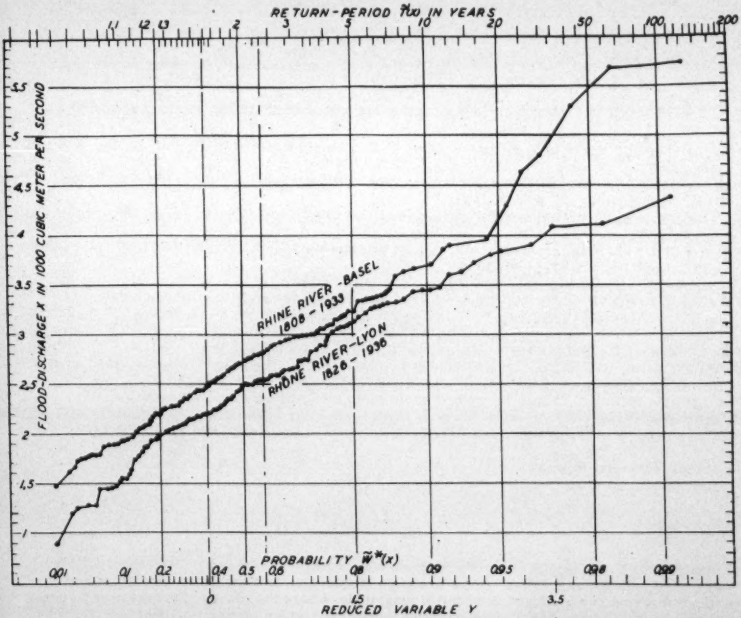

Fig. 10--Adjusted return-periods, Rhine River, Basel 1808-1933, and Rhône River, Lyon 1826-1936

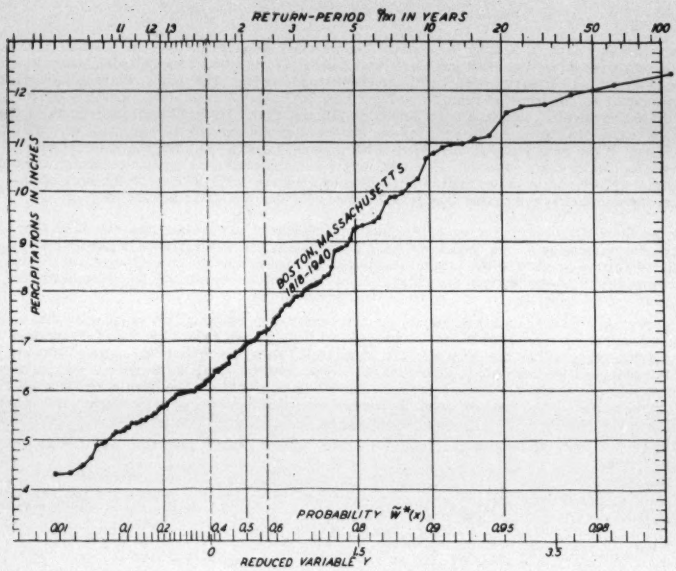

Fig. 11--Adjusted return-periods, monthly largest precipitations, Boston, 1818-1940

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DISCUSSION

BRADFORD F. KIMBALL (Port Washington, New York)--This paper by Professor Gumbel answers the fundamental question of how to assign frequencies to a series of equally weighted statistical observations arranged in order of magnitude, where the series of events may be considered as a sample from an infinite population subject to a given probability-law.

The effective solution of this problem is made possible by the introduction of a formula for the probability-distribution of the m'th observation [see equation (7)]. This equation should be thoroughly understood if the deductions from it are to be convincing. As presented, the meaning of $[v_n(m,x)]$ is that $[v_n(m,x)]\,dx$ represents the probability that the m'th observation in a series of n observations ordered by magnitude will have a measure x.

As Gumbel indicated in his paper in these Transactions in 1942 [see 4 of "References" at end of Gumbel's paper], this expression is obtained by considering the m'th observation as lying between the $(m-1)^{th}$ and the $(m+1)^{st}$. If in a series of (n - 1) observations, (m - 1) are less than x and (n - m) greater than x, the probability of this arrangement is

$$\binom{n-1}{m-1} W^{(m-1)} (1-W)^{(n-m)}$$

The remaining n'th observation which is to lie at x may be chosen in n different ways and the probability that one random observation lies at x is given by w (x) dx. Hence

$$v_n(m,x)\,dx = \binom{n-1}{m-1} W^{(m-1)} (1-W)^{(n-m)} \times n w\,dx$$

If any further doubts arise as to the correctness of this formula, two further tests may be applied.

If the formula gives a true probability-distribution, then for constant m and n

$$\int v_n(m,x)\,dx = 1$$

where integral is taken from W = 0 to W = 1. If W be taken as variable of integration s, then ds = w dx and we have

$$v_n(m,x)\,dx = \binom{n-1}{m-1} n \int_0^1 s^{(m-1)} (1-s)^{(n-m)}\,ds$$

The integral on the right is recognized as the Beta function $[B(m, n-m+1)] = [\Gamma(m)\,\Gamma(n-m+1)/\Gamma(n+1)] = (m-1)!\,(n-m)!/n!$ which is the reciprocal of $\binom{n-1}{m-1} n$ and thus the integral has value one.

The second test is to hold x constant and let m take on all values from 1 to n. This finite sum should give the probability that at least one of n observations would lie at x. Thus this sum should equal [nw (x) dx]. This is clearly the case since

$$\sum_{m=1}^{n} \binom{n-1}{m-1} W^{(m-1)} (1-W)^{(n-m)} = (W + 1 - W)^{(n-1)} = 1$$

Professor Gumbel then maximizes $[v_n(m,x)]$ by setting the derivative of $[v_n(m,x)]$ as to x equal to zero. This gives equations [after division by w (x)] which appear as (10) and (11). The meaning of these equations should now be clear. They determine the value of the measure x which is most likely to occur, as the m'th value, in a series of n observations.

To this most likely value of x there corresponds a value W (x) which is thus taken as the most probable, or "best" frequency, to be assigned to the m'th observation and denoted as W. From that point on the paper considers various approximations for W in terms of m and n as deduced from equations (10) and (11).

For annual floods the probability-distribution gives

$$\Delta = -[(1-\tilde{W})/\ln \tilde{W}]$$

and for the extreme observed flood, with m = n, Gumbel shows that

$$\tilde{W} = \mathrm{Exp}(-1/n)$$

and accordingly the corresponding return-period converges to (n + 1/2) for large n.

This is a very interesting answer to the question left hanging in the air last year [4, p. 501, third paragraph], and the reasoning by which this answer is obtained appears to the writer to be conclusive.

R. S. GOODRIDGE (Federal Power Commission, Washington, D. C.)--The Section of Hydrology has again been favored by a timely and valued contribution from Professor Gumbel.

Two important additions to previous works of the author [see his references 2, 3, and 4] enhance their value through the provision of better mechanical tools for the general application of their results. These tools are (1) the design of a functional probability-paper such that the distribution may be fitted by a straight line, and (2) the rigorous development of the plotting positions of the individual events comprising the array of the floods. Professor Gumbel has pointed out that this method gives the best plotting position for any distribution and will be of value for the normal, the exponential, Hazen's, and other distributions, skewed or symmetrical, which are found in meteorology, hydrology, and other fields.

These two mechanisms supplant the need for the tables suggested by the writer in discussion of Professor Gumbel's paper in the Transactions of 1942. However, the tables would be of value to other workers in mathematical fields and for further work in developing the adaptability of this theory to other arrays, as for use with the basic-stage level.

Having the functional probability-paper and the concise and direct plotting-position relations, the hydrologist, engineer, or economist need only calculate the two constants of the distribution, namely, u, the most probable annual flood, and $(1/\alpha)$, the slope of the line of best fit. The constants are then introduced in equation $x = u + (y/\alpha)$, where x is the flood-discharge and y is a reduced variable without dimension by linear transformation equal to $\alpha(x - u)$. To calculate the terminal discharges for the plotting-points defining the straight line of best fit, x may be determined for values of y equal to -2 and 7, which are equivalent to the return-periods, $T_{(x)}$, nearly equal to 1 and 1,100. It is proposed that a light line be placed on the paper at an abscissa 7, similar to -2.

To summarize, the following five steps are required to complete the determination of the constants:

$$(A)\ \bar{u} = (1/n) \sum_{m=1}^{n} x_m$$

$$(B)\ \overline{u^2} = (1/n) \sum_{m=1}^{n} x_m^2$$

$$(C)\ s = \sqrt{[1 + 1/(n + 1)]\ (\overline{u^2} - \bar{u}^2)}$$

$$(D)\ (1/\alpha) = 0.77970s$$

$$(E)\ u = \bar{u} - (0.57722/\alpha)$$

where $\bar{u}$ is the arithmetic mean of flood-events x_m, n is the number of flood-events, s is the standard deviation, and $\overline{u^2}$ is the average of flood-events squared.

Emphasis should be placed on the general utility of the distribution-function developed from the classical theory of the largest of n values by Professor Gumbel. It may be applied to the analysis of data other than floods, such as temperatures, droughts, damages from flood-hazards of various kinds, as by seasons, with respect to the various conditions of crops, etc., events having irregular or periodic occurrences.

The theory has been regularly employed by the writer during the past year in fitting curves to arrays of flood-magnitudes with use of "experience-ceilings", functional flood-indices, presented in discussion by the writer last year. The "ceilings" for the extreme extrapolated range of the theoretical curve are set, tentatively, at a more or less arbitrarily determined average occurrence-interval in years, as say, once in 4,000 to 10,000 years. An appropriate position is indicated by use of a curvilinear line joining the "ceiling" with the extrapolated theoretical curve at an appropriate multiple of the record-period in years. A useful "ceiling", when available, is the flood resulting from the so-called maximum-possible storm as determined by hydrometeorological methodology under development by the Hydrometeorological Section of the United States Weather Bureau and used by the United States Engineers for the safe capacity of the spillways of dams.

This treatment serves to guide the designer of spillways, "fuse-plugs", and other engineering works, in the provision to be made for the possible but rare flood-events, within practical and economic limitations, with cognizance of such events and the consequences which would result should the capacity provided be exceeded.

During the past year the writer communicated to the author his practice with the method for arrays of flood-events comprising all the floods above a basic-stage level, as for out-of-bank floods causing inundation-damages. The solution is made for the total number of the individual events without regard to the time in years during which the array was observed. The theoretical curve is then adjusted from events to time in years by use of the relation (Y/n), where Y is the total number of years of record and n is the total number of the observed floods. (Y/n), as a multiplier, converts the occurrence-scale of events to the occurrence scale in years. In this manner any array may be prepared as desired. The expression required for the rigorous mathematical presentation of the arrays so formed may be a subject for a future work of Professor Gumbel.

Sufficient progress has now been made to consider the provisions which may be made for the printing of the functional probability-paper, preferably by a commercial company dealing with graph-paper.

Two sizes are desirable--one 8.5 by 11 inches, the single sheet, and another, 11 by 16 inches, the double sheet. The ordinates for both sheets would range over the shorter dimension and have uniform divisions of 100 over 7 inches and 140 over 10 inches, respectively, with the fifth and tenth lines heavy, and graduated. No printing of scales or descriptive notation would appear on the ordinate margins as the paper is for general use and can be marked by the individual users for a variety of selected ranges. The abscissas, on the long dimension, would be designated "Probable occurrence-interval in years" and range from 1.001 to 1,000 years over nine linear inches on the single sheet and from 1.001 to 10,000 years over about 15 linear inches on the double sheet, an increase of about 29 per cent in the openness of the scale in the longer sheet. Emphasis should be given to the scale "Probable occurrence in years", called by Professor Gumbel "Return-period, T(x), in years", that is, the through-lines should be made to show the probable flood expected, on the average, once in 15, 30, 35, 45, etc., years in appropriately graduated intervals. The probability and the reduced interval (Y-) scales could be marginally marked, in smaller type, only as a guide for reference when such expression is desired, except for the values -2 and 7, which should be shown in a thin line to guide in the plotting of the terminal values of the calculated discharges on the theoretical straight line. All the scales for abscissa can be printed.

It will be observed that the writer proposes that the term "Probable-occurrence interval in years", be used. This is made with cognizance of the "Remarks on hydrologic terminology" contributed last year by Dr. ROBERT E. HORTON. Professor Gumbel's curve is neither the exceedance- nor the recurrence-curve; it lies between the two, approximating the exceedance-curve in the lower range from unity and approaching the recurrence-curve in the upper range. In view of this property the term "occurrence" appears to be the most logical, in the mathematical sense.

FORECASTING SEASONAL RUNOFF BY STATISTICAL METHODS

Phillip Light and Max A. Kohler

Introduction

In a paper entitled "Progress toward a rational program of snow-melt forecasting [see 1 of "References" at end of paper] MERRILL BERNARD outlined and presented graphically the relations between the factors involved in the snow-melt phenomenon. This outline is an expression of a forecasting-procedure development for which this paper may be considered a progress-report.

The undertaking is made in full knowledge of the limitations of precipitation as a quantitative expression of subsequent runoff. It is, however, fortified with the essential element in the development of any statistical method, namely, relatively long periods of record. The first attempts have been encouraging and are presented here in some detail. The Rio Grande above Elephant Butte has been selected for the demonstration because of the clear necessity there for quantitative water-supply forecasting, and because of the availability of organized data [2].

There have been many attempts made in the past to correlate precipitation during the winter with runoff during the melting season. The reader is referred to papers on the subject by ALTER

[3], MELIN [4], DEBLER and JOHNSON [5], REEDY [6], ELGES [7], and BOARDMAN [8]. The forecasting procedure described by Alter utilized a 21-year record of precipitation, snow-surveys, and runoff for several watersheds near Salt Lake City, Utah. Alter showed that if the procedure had been based on a percentage-relation between October-to-March precipitation and April-to-July runoff, the results would have been comparable to those based on April 1 snow-surveys. Melin made a statistical analysis of precipitation and runoff-data and obtained linear regression-equations between total spring runoff and precipitation, and between peak-flow in the spring and precipitation for six snow-covered basins in northern Sweden. He considered the correlation-coefficients to be sufficiently high to warrant the use of these equations for forecasting purposes.

It is well known that the percentage-of-normal method of seasonal forecasting, based either on snow-survey or precipitation-data, occasionally results in wide divergence between predicted and observed amounts. These deviations are commonly ascribed to various unaccounted-for influences, such as soil-priming, additional precipitation during the runoff-period, abnormal losses, etc. CHURCH [9] has given an excellent description of these effects and has indicated qualitatively the errors that result in forecasts based wholly on snow-cover measurements.

In the investigations described in this paper the attempt has been made to evaluate the predictable influences by means of a statistical correlation-procedure. The use of concurrent long-period records of precipitation and stream-flow will, it is believed, justify such a procedure. The introduction of variables in addition to winter precipitation should then considerably improve the verification of the forecasts.

Preliminary studies

Reasonable evidence of a rational relationship between the principal factors involved in the creation of seasonal runoff from melting snow became a basic criterion in the selection of factors for the statistical correlations. Accordingly, two basic relations were adopted:

Snow-cover = Winter snowfall – snowpack-losses
Spring runoff = Snow-cover – soil-moisture deficiency + post-seasonal snowpack-gains

The term "snow-cover" represents the quantity of snow on the ground immediately prior to active runoff. While evapo-transpiration losses and rainfall during the late spring and early summer may be significant factors in some localities, they were here disregarded because of their obvious lack of forecasting value. The further development of long-range forecasting of weather may make it possible to include these factors ultimately.

It is impossible, on the basis of available data, to evaluate any of the factors in the above equations in terms of volume or average depth over the watershed, and from a statistical standpoint it is unnecessary. In a multiple correlation, each term can be represented by an appropriate index. The following series of indices, selected partly on the basis of available data and partly for their forecasting value, were considered.

Term	Index
Winter snowfall	Accumulated winter precipitation
Snowpack-losses (evaporation and pre-seasonal melting)	Winter temperature
Soil-moisture deficiency	Fall precipitation or winter runoff
Post-seasonal snowpack-gains	April precipitation and April temperature

April temperature was introduced in addition to April precipitation as an index to early post-seasonal snowpack-gains because the relative amounts of snowfall and rainfall in April are important. A further discussion of this effect will follow later.

Preliminary calculations were made for the Pecos and Gardiner rivers and consisted of correlations of monthly runoff at a single stream-gaging station with concurrent monthly precipitation and temperature at a single Weather Bureau station. The periods of record used in these analyses were 31 years and 19 years, respectively. Various independent variables were selected, using the above table as a guide, and individually correlated with spring runoff. The correlation-coefficients for the significant variables representing each of the above indices are shown below.

Variable	Gardiner Basin	Pecos Basin
November-March precipitation	0.85	0.62
January-March temperature	0.02	-0.40
October precipitation	0.13	0.26
February runoff	0.41	0.32
April temperature	-0.31	-0.43
April precipitation	0.38	0.58

It can be seen that winter precipitation is the most important factor, as was expected. Winter temperature, although apparently important on the Pecos, was found to be inversely correlated with winter precipitation. In other words, there have been a considerable number of years of concurrent heavy precipitation and low temperature during the winter season, as well as the reverse of these conditions. On the basis of the preliminary study, therefore, the number of significant variables used in the Rio Grande study was reduced to four, namely: Winter precipitation; fall precipitation (or winter runoff); April precipitation; and April temperature.

The Upper Rio Grande Watershed

The Upper Rio Grande Watershed, shown in Figure 1, is defined here as the contributing drainage-area of approximately 26,000 square miles above Elephant Butte Dam. It produces the greater portion of runoff of the entire Rio Grande Basin, which embraces an area of 175,000 square miles. The upper basin is bounded on the west by the main range of the Rockies and on the east by the Sangre de Cristo Mountains. From a minimum elevation of 4,300 feet in the valley, the mountains on either side rise to heights of 10,000 to 14,000 feet. A low divide across the northern portion, in Colorado, separates an undrained plateau area known as the Closed Basin.

Mean annual precipitation varies from nine inches in the southern portion of the valley to above 40 inches in the headwaters. In general, contributions of precipitation and runoff decrease in the downstream direction. The heaviest precipitation in the valley occurs during the summer months whereas at high elevations the maximum is reached during the winter season. Large-scale frontal systems traveling westward from the Pacific Coast in the winter produce wide-spread snowstorms at high elevations. The deposit of snow from each storm assumes a characteristic distribution that produces a reasonably similar pattern of snow-accumulation every season. On the other hand, rainfall during the summer is extremely spotty, in that unstable air flowing in from the Gulf of Mexico produces storms characterized by scattered convectional rains. Occasionally, heavy cloudbursts in the summer will cause flash floods in the tributaries but these have only a minor effect on total annual runoff of the whole basin. Approximately 70 per cent of the annual runoff is due to melting snow stored in the mountainous area above 8,000 feet. These waters reach the lower irrigated areas during April, May, June, and July.

The greatest concentration of irrigated lands is in the valley north of the Colorado-New Mexico State Line, known as the San Luis Section. In the remainder of the Upper Rio Grande Basin, most of the diversion takes place along the main stream with minor amounts between the Colorado State Line and Otowi Bridge, and larger diversions from that point to San Marcial at the entrance to Elephant Butte Reservoir.

Important water-contributing areas (see Fig. 1) are the heavy snow-covered region in the northwest part of the basin along the Continental Divide, and the mountainous strip on the east side of the river. The southeast portion of the San Luis Section is unimportant to a forecasting procedure serving downstream points because practically all of the runoff in that area is consumed before it enters the main stream. Other important portions of the basin to be considered are the catchment-area above the storage-reservoirs, the largest of which are Elephant Butte on the Rio Grande with a capacity of 2,600,000 acre-feet, and El Vado on the Rio Chama of capacity 200,000 acre-feet.

Character of data

For convenience of tabulation and computation, it was decided to use data in the form of monthly totals or averages although it is believed that eventually some improvement in correlation may result from the adoption of a shorter time-increment. Sources of stream-flow data include records of the United States Geological Survey and the State Engineers of New Mexico and Colorado. Full use was made of the National Resources Committee report for the Upper Rio Grande [2], where estimated values of discharge are given for many missing periods. Table 1 lists the important stream-gaging records in the area, the station-locations for which are shown in Figure 1. These stations are in existence at the present time, have long periods of records, and measure significant

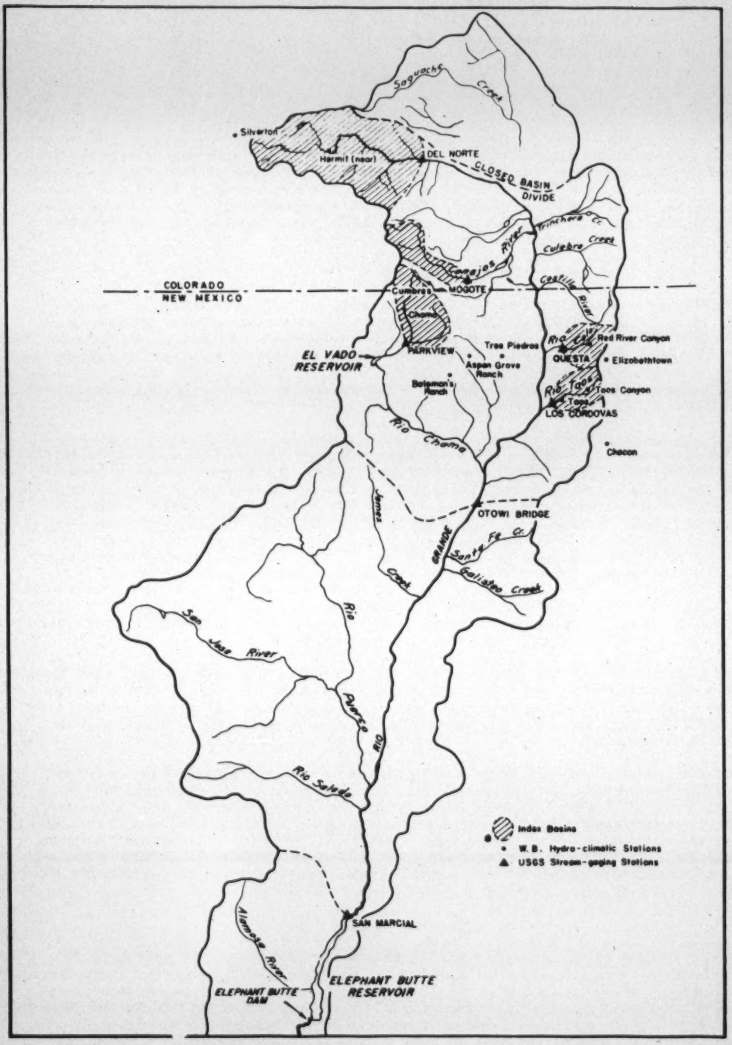


Fig. 1--Map of Upper Rio Grande Watershed

Table 1--Stream-gaging stations, Upper Rio Grande Basin

Stream	Gage	Area	Period record	Mean annual flow
		sq mi		acre-feet
Rio Grande	Thirty-mile Bridge, Colorado	163	1911-23;1927-	.....
	Wason, Colorado	700	1890-	451,000
	Del Norte, Colorado	1320	1890-	707,000
	Alamosa, Colorado	1712	1890-	287,000
	Lobatos, Colorado	4800	1890-	550,000
	Embudo, New Mexico	7327	1890-	860,000
	Otowi Bridge, New Mexico	11303	1890-	1,353,000
	San Marcial, New Mexico	24176	1890-	1,128,000
Alamosa Creek	Terrace Reservoir, Colorado	120	1915,1917-20,1922-	.....
Conejos River	Mogote, Colorado	282	1890-	256,000
	La Sauses, Colorado	887	1911-	190,000
San Antonio	Manassa, Colorado	348	1911-	71,000
Culebra Creek	San Luis, Colorado	220	1909-19;1927-	.....
Rio Colorado	Questa, New Mexico	112	1913,1915-25,1927-	.....
Rio Taos	Los Cordovas, New Mexico	359	1910-25,1927-	.....
Rio Chama	Park View, New Mexico	405	1913-15,1925-	.....
	Chamita, New Mexico	3202	1913-	.....

Table 2--Hydro-climatic stations, Upper Rio Grande Basin

Station	Elevation	Period record	Mean annual precip.
	ft		inch
Silverton, Colorado[a]	9400	1907-	26.0
Hermit, Colorado[a]	8912	1899-1900,1910-	17.4
Cumbres, Colorado	10015	1891-92,1910-	32.0
Chama, New Mexico[a]	7851	1889-97,1905-	22.3
Aspen Grove Ranch	9000	1909-	23.4
Selsor Ranch, New Mexico	8500	1912-	22.0
La Veta Pass, Colorado	9242	1909-	21.4
North Lake, Colorado	8700	1890-1906,1909-19,1924-	22.2
Red River Canyon, New Mexico[a]	8956	1906-	22.2
Elizabethtown, New Mexico[a]	8465	1905-	17.2
Taos Canyon, New Mexico	8959	1909-	19.8
Taos, New Mexico[a]	6983	1889-96,1901-	12.9
Chacon, New Mexico	8510	1909-	20.5
Winsors Ranch, New Mexico	8000	1895-	24.5
Santa Fe, New Mexico	7013	1850-	14.4

[a]Temperature data also available.

amounts of spring flow. Table 1 gives also a basis of comparison of snow-melt contribution between basins in terms of annual flow. It may be noted that the Conejos River near Mogote, Colorado, shows the greatest annual runoff per square mile.

The important stations, which record precipitation and temperature, selected for this study are listed in Table 2, and are shown in Figure 1. These were selected because of their availability for service use, representativeness as to location and elevation, and length of record. Temperature-data are available at seven out of a total of 18 stations. The sources of data are the monthly and annual climatological summaries issued by the Weather Bureau.

Adjustment of observations

There are two known sources of error in the use of precipitation-data as a measure of accumulated snowfall. First, deficiencies in precipitation attributable to the effect of wind on the catch and second, changes in conditions of location or exposure throughout the life of the station. The general use of shielded storage-gages is expected to obviate the first difficulty; however, since present methods for sampling snow, either as it falls or as it lies on the ground, have decided statistical limitations as an expression of average depth over a watershed, values by this method can be considered no more than an index. So used, it is found that systematic errors of observation have only a minor effect on the accuracy of the results. The second source of

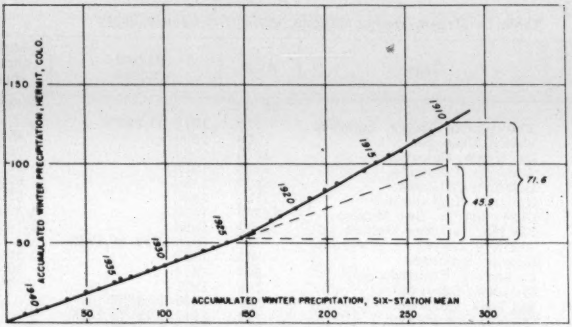


Fig. 2--Adjustment of past records of precipitation at Hermit (near)

error is more serious and presents the need for some method of adjustment, particularly in mountainous country where slight changes in location appreciably affect the measurement of snowfall [10]. The adopted method of adjustment is based upon a procedure that compares the accumulated precipitation at the station to be tested with the corresponding accumulated values of mean precipitation for a group of stations within the zone of its environment [11].

In certain cases a decided change in station regime was indicated by an abrupt change in the slope of a line representing cumulative depth, as illustrated in Figure 2. This apparent change in the precipitation regime is accounted for by the fact that in this case the station was moved from Hermit to near Hermit in 1923. Therefore, on the basis of the difference in slope of the two sections of the curve, the records for Hermit were adjusted by the factor (45.9/71.6) to make the earlier years comparable with those for the present station, near Hermit. By similar analyses, it was found that several of the remaining stations required adjustment. Wherever possible the station-histories were investigated in order to verify the change in circumstances disclosed by the graph.

Temperature-data were subjected to the same analysis but no marked variations were indicated. Changes in location of station do not materially affect the values of mean monthly temperature unless considerable change in elevation is involved.

A relatively large amount of potential storage is available on the Rio Grande above Del Norte. Since diversions in this basin are relatively small, measured runoff, corrected for change in artificial storage, was assumed to very nearly represent natural runoff. Artificial storage is not significant in any of the remaining tributary-basins. Diversions, however, may be of some significance in tributaries on the eastern side of the Rio Grande, but were disregarded in this study because of lack of quantitative information.

A forecast of seasonal flow, to be of greatest value, should be in terms of measured discharge at a station representing the area to be served, since the actual flow past the gage is the important factor to water-users downstream. In order to obtain comparable runoff-data for as long a period as possible, resort was made to runoff-data published in the National Resources Committee Report [2] based on irrigation-developments existing in 1935. The extent of irrigation had been fairly constant from 1927 to 1935 and it is assumed that in succeeding years no material change has occurred. However, if a large-scale expansion of the irrigated area takes place in the future, the forecasting relations would necessarily have to be modified.

Selection of tributary-basins

Forecasting procedures were developed for tributary-basins for two reasons: First, for their individual value to the interests of irrigation and water-supply to be served; and second, in order that the tributary might serve as an index to runoff at stations downstream. The most significant factors determining the feasibility of developing a procedure for a given basin are: Quantity of snow-melt runoff; length of available records; character of storage and diversion; and

number of precipitation- and temperature-stations in or near the basin. Any attempt to forecast April-to-July runoff would obviously be futile unless a great percentage of the runoff occurring in that period is the result of snow-melt. An examination of records of discharge and precipitation will serve to identify areas of significant snow-melt runoff. In most of the mountainous regions of the West there are a sufficient number of hydroclimatic stations with relatively long periods of record, as compared to stream-gaging stations. Therefore, the length of the discharge-record will usually govern the period covered by the analysis. In the Rio Grande analysis, the periods of record employed in the various correlations were as follows: Rio Grande near Del Norte, 32 years; Rio Grande at Otowi Bridge, 32 years; Rio Grande at San Marcial, 32 years; Conejos River at Mogote, 32 years; Rio Colorado at Questa, 27 years; Rio Taos at Los Cordovas, 28 years; and Rio Chama at Park View, 20 years. Tributary-basins selected as index-basins should preferably have little or no diversion and storage-capacity. For this reason, it was necessary to forego the use of several of the longer records of stream-flow. Because of the brief discharge-record at Park View, the Rio Chama was not utilized as an index-basin. However, a forecasting relation was developed for that basin because the flow at that point represents essentially the inflow into El Vado Reservoir.

Correlation of runoff with winter precipitation

The first step in the correlation-process was to determine the effect on runoff of the most important single variable--winter precipitation. In selecting precipitation-stations it is to be expected that certain stations should prove to be better indices to runoff within a particular basin than others because of their location, elevation, quality of data, etc. It is reasonable to suppose that a station centrally situated and at an elevation high enough to be representative of conditions within the snow-field is superior to one that fails to meet these requirements.

The seasonal runoff, April to July, in each of the five tributary-basins selected, was correlated with winter precipitation at stations in the vicinity of the respective basins. Table 3 gives the correlation-coefficients for the relations between November-to-March precipitation and seasonal runoff, and between December-to-March precipitation and seasonal runoff, for each basin. On the basis of the relative value of correlation-coefficients a selection was made of station-groups and significant snow-storage periods best suited to the needs of each basin. It may be noted that November-to-March precipitation in almost every case yields the best correlation. This period was therefore adopted as the period of winter precipitation in all cases.

From Table 3 it is seen that larger correlation-coefficients can be obtained on the western side of the Upper Rio Grande Basin than on the eastern side. This would indicate that the flow from the two eastern basins is more erratic. An explanation for this might be that since a lesser quantity of snow is deposited along the Sangre de Cristo Range, the relative influence of spring precipitation there is more pronounced. Another possible reason is the effect of relatively heavier diversion in that section of the watershed.

Table 3--Correlation-coefficients between winter precipitation at single stations and April-July runoff

Station	Rio Grande near Del Norte		Conejos at Mogote		Rio Chama at Park View		Rio Colorado near Questa		Rio Taos at Los Cordovas	
	Dec.-March	Nov.-March	Dec.-March	Nov.-March	Dec.-March	Nov.-March	Dec.-March	Nov.-March	Dec.-March	Nov.-March
Silverton	.50	.57[a]	....	....	....	....	....	....	....	....
Hermit	.56	.66[a]	.58	.55	....	....	....	....	....	....
Cumbres	....	....	.68	.70[a]	.70	.74	....	....	....	....
Chama	....	....	.54	.59[a]	.81	.82[a]	....	....	....	....
Aspen Grove Ranch	....	....	....	....	.80	.82[a]	....	....	....	....
Tres Piedras	....	....	....	....	.61	.72	....	....	....	....
Batemans Ranch	....	....	....	....	.70	.76	....	....	....	....
Red River Canyon	....	....	....	....	....	....	.42	.42[a]	.38	.43
Elizabethtown	....	....	....	....	....	....	.25	.28	.30	.42[a]
Taos Canyon	....	....	....	....	....	....	.44	.41[a]	.54	.62[a]
Taos	....	....	....	....	....	....	....	....	.55	.56[a]
Chacon	....	....	....	....	....	....	....	....	.42	.52

[a]Used in final correlation.

It is interesting to note that the influence of proximity of station mentioned previously is verified in Table 3. The Table shows, generally, a decrease in the value of the correlation-coefficient with increasing distance between the precipitation-station and the basin. MONSON [12] made a similar correlation between snow-survey measurements and runoff and found the same effect. In a few cases, notably Silverton, the stations are situated on the opposite slopes of the ridge and therefore yield a lower correlation.

In order to improve the correlation of precipitation with runoff and to obtain a greater security in the resulting relations, it was decided to use a combination of stations. An arithmetic sum fails to serve because it gives too much weight to stations with high seasonal precipitation and to stations with inferior correlation-values. Assigning weights by means of elevations of station and relationships of elevation to area of basin is impossible because of the limited number of high-altitude stations. A weighting procedure based on a multiple correlation avoids these weaknesses. Accordingly, linear regression-equations were developed on the basis of station pairs, with the results shown in Table 4. The regression-coefficients are expressed as simple ratios and converted

Table 4--Linear regression-equations between winter precipitation at paired stations and April-July runoff

Basin	Regression-equation,[a] Q =	Multiple correlation-coefficient	Weighting-factors
Rio Grande near Del Norte	144 + 1.4 (Silverton) + 6.2 (Hermit)	.69	2:9
Conejos River at Mogote	44 + 6.7 (Cumbres) + 4.1 (Chama)	.72	3:2
Rio Chama at Park View	-33 + 15.5 (Chama) + 16.6 (Aspen Grove Ranch)	.86	1:1
Rio Colorado near Questa	-2 + 2.8 (Red River Canyon) + 3.2 (Taos Canyon)	.47	1:1
Rio Taos at Los Cordovas	-19 + 7.4 (Taos Canyon) + 2.6 (Taos)	.62	3:1

[a] Q = April-July runoff in 1000 acre-feet.

to weighting-factors. These approximate weights are considered sufficiently accurate for the purpose and were used in succeeding computations. A correlation involving more than two stations showed an insignificant improvement over a pair of stations. This is to be expected, since the inclusion of more stations results in the use of observations made at a considerable distance from the area of interest. However, if additional stations had been available within a basin, these records would naturally have been utilized.

Development of forecasting charts

In developing a forecasting procedure involving more than two variables it is found convenient to use a graphical procedure in that curvilinear relations can be developed without undue labor. Multiple curvilinear correlations by analytical methods require either a prior knowledge or the assumption of specific functional relationships and usually involve a series of quite lengthy computations.

The method used to accomplish the graphical relation will not be discussed in detail since it is identical with the method so adequately described and illustrated by EZEKIEL [13]. The independent variables are introduced one at a time--each being plotted against the residuals from the approximation of the previous regression; thus the first approximation of all net regressions is obtained. This process is repeated and successive approximations are obtained until a point is reached where no further improvement in correlation results. In this case, the final series of net regressions represents the forecasting relations, and is expressed as a single graph relating the principal independent variable to seasonal runoff, together with a family of correction or modifying curves giving values which account for the effects of secondary factors.

Weighted precipitation in winter, as developed previously, is the principal independent variable for the tributary-basin correlations. Since winter temperatures and precipitation are interdependent as explained previously, no material improvement in correlation results from the use of a winter variable of temperature. Pre-seasonal melting is not of great importance in the Rio Grande Basin as indicated by the fact that very little runoff occurs during the winter season.

Hence, weighted precipitation in winter alone is taken as the index to the quantity of snow on the ground at the beginning of the melting-season. In regions where evaporation may remove a considerable portion of the snow-cover or where winter runoff is significant, some attempt should be made to determine a factor to represent these influences.

Several possible indices are immediately apparent for a representation of soil-moisture deficiency. Fall precipitation, water-level observations in wells, flow of perennial springs, and winter discharge have been used by other investigators. In the case of the Upper Rio Grande, it was found that minimum monthly (calendar) stream-flow, November to March, gave a good indication of soil-conditions, and was used wherever such data were available. When winter discharge-data were not available for tributary-basins, fall precipitation was substituted. It was found that bimonthly precipitation from September to October, weighted by applying the same factors as for winter precipitation, yielded the best results.

Winter precipitation and fall precipitation (or minimum monthly runoff) are the two factors used for forecasting seasonal flow on April 1. Forecasts made on May 1 can, of course, take into account conditions prevailing during the month of April which tend to modify subsequent runoff. April temperature and April precipitation were both found to have potent influences on spring runoff. April temperature has an inverse effect so that seasons characterized by low April temperatures tend to produce more runoff than is indicated by winter precipitation. This is undoubtedly due to the fact that when the average temperature in April is below normal, an above-normal percentage of the precipitation occurs as snow during that month. To improve the security of the forecast of May 1, the mean April temperature of several stations was used.

The results for the five tributary basins are shown in Figures 3A, 3B, 3C, 4A, and 4B. The first three figures represent the forecasting charts for the three western basins. Separate winter precipitation regression-lines are shown for the forecasts of April 1 and May 1 because the inclusion of the two additional variables, April precipitation and temperature, has a tendency to change the slope of this line. For the two eastern tributary-basins, the change in slope is insignificant, and therefore the same curve is used for both forecasts. Curves for both minimum monthly runoff and fall precipitation, on the right-hand side of the graphs, flatten off at the upper end indicating the characteristic effect of soil-saturation. It will also be noted that April temperature shows a leveling off, but in this case at the low values.

As an example of the use of these charts, assume the following values for the Rio Grande above Del Norte: Weighted winter precipitation = 80.0 inches; minimum monthly runoff = 16,000 acre-feet; weighted April precipitation = 16 inches; and mean April temperature = 40°. For a forecast on April 1, enter left-hand graph at 80.0 inches and read 710,000 acre-feet off the regression-line of April 1. Enter scale (1) on right-hand graph at 16,000 acre-feet and read correction value of +30,000 acre-feet. The sum of the two values, 740,000 acre-feet, would be the predicted runoff as of April 1. For a forecast on May 1 the same procedure would be followed, except that the winter precipitation regression-line of May 1 would be used and the correction to be applied would be the algebraic sum of the values read from curves (1), (2), and (3)--in this case 650,000 acre-feet.

The forecasts for the lower reaches of the Upper Rio Grande are based on a different principle than the forecasts for the tributary-basins. Correlations of runoff at the downstream gages with precipitation and temperature for numerous stations within large drainage-areas could have been made; however, the procedure would have been extremely cumbersome. The use of a flow-assembly procedure in which the runoff from the headwater-basins are properly weighted and combined to give the resultant flow downstream has proven to be more logical and is accomplished through a simple procedure. An advantage of a forecast-procedure based on runoff from index-basins lies in the fact that a single relation may be developed which is applicable for forecasts issued at any desired time. In this way the "overall" forecasting plan for the whole basin becomes comparable to rather well-established forecasting procedures in which crest-stages for headwater-stations are predicted directly from precipitation-data, and stages for the lower reaches are predicted from upstream-stages.

In accordance with this plan the runoff at Otowi Bridge was related to the runoff at four index-basins as shown in Figure 4C. The Conejos River above Mogote was found to be the most important index to Otowi Bridge flow, a fact which may be accounted for by the comparatively heavy runoff from that area. Consumptive use for a particular locality during any one season is principally limited by the established irrigated areas. Therefore, a larger proportion of the water-yield is released during wet years than during dry years. This will tend to produce the type of curvature shown in the left-hand graph of Figure 4C. This effect is also present for all correction-

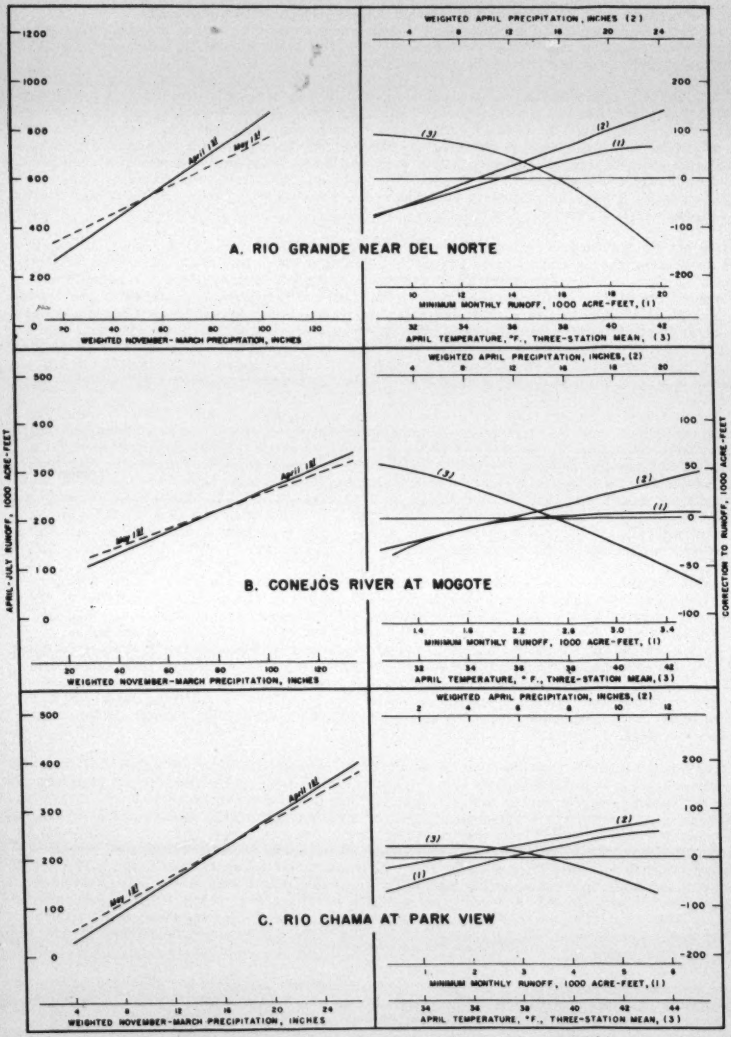

A. RIO GRANDE NEAR DEL NORTE
B. CONEJÓS RIVER AT MOGOTE
C. RIO CHAMA AT PARK VIEW
APRIL - JULY RUNOFF, 1000 ACRE-FEET
CORRECTION TO RUNOFF, 1000 ACRE-FEET
WEIGHTED NOVEMBER - MARCH PRECIPITATION, INCHES
WEIGHTED APRIL PRECIPITATION, INCHES (2)
MINIMUM MONTHLY RUNOFF, 1000 ACRE-FEET, (1)
APRIL TEMPERATURE, °F., THREE-STATION MEAN, (3)
April 1st
May 1st
(1)
(2)
(3)

Fig. 3--Forecasting charts--Del Norte, Mogote, and Park View

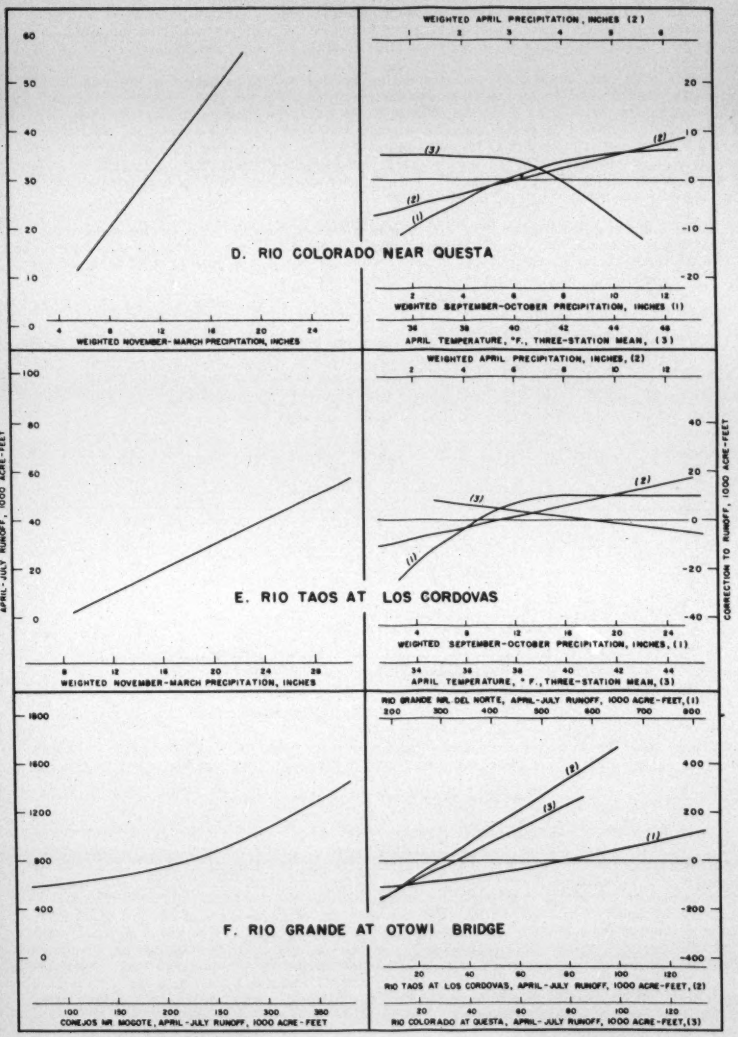

D. RIO COLORADO NEAR QUESTA
WEIGHTED NOVEMBER-MARCH PRECIPITATION, INCHES
WEIGHTED APRIL PRECIPITATION, INCHES (2)
WEIGHTED SEPTEMBER-OCTOBER PRECIPITATION, INCHES (1)
APRIL TEMPERATURE, °F., THREE-STATION MEAN, (3)
E. RIO TAOS AT LOS CORDOVAS
APRIL-JULY RUNOFF, 1000 ACRE-FEET
CORRECTION TO RUNOFF, 1000 ACRE-FEET
WEIGHTED NOVEMBER-MARCH PRECIPITATION, INCHES
WEIGHTED APRIL PRECIPITATION, INCHES, (2)
WEIGHTED SEPTEMBER-OCTOBER PRECIPITATION, INCHES, (1)
APRIL TEMPERATURE, ° F., THREE-STATION MEAN, (3)
F. RIO GRANDE AT OTOWI BRIDGE
CONEJOS NR MOGOTE, APRIL-JULY RUNOFF, 1000 ACRE-FEET
RIO GRANDE NR. DEL NORTE, APRIL-JULY RUNOFF, 1000 ACRE-FEET, (1)
RIO TAOS AT LOS CORDOVAS, APRIL-JULY RUNOFF, 1000 ACRE-FEET, (2)
RIO COLORADO AT QUESTA, APRIL-JULY RUNOFF, 1000 ACRE-FEET, (3)

Fig. 4--Forecasting charts--Questa, Los Cordovas, and Otowi Bridge

curves but since it was not so marked for the two eastern basins, straight lines were adopted in those cases. In the use of the Otowi-Bridge graph, forecasted values taken from the index-basin charts may be used in Figure 4C in obtaining either April 1 or May 1 forecasts.

As was expected, a high degree of correlation was discovered between the flow past Otowi Bridge and that at San Marcial. The runoff-relation between the two gages, shown in Figure 5, is based on 52 years of record. It will be noted in Table 1 that the average annual flow at San Marcial is less than the annual flow of the upstream-station, Otowi Bridge, which shows that the water diverted in the reach is greater than the local inflow. Variations in inflow are masked by the considerable diversion within this reach of the river and therefore it was found unnecessary to include an added inflow-factor in the correlation. A correlation-coefficient of 0.94 was obtained for the simple relation between runoff at the two gages.

In the interest of timeliness and the reduction of errors it should be desirable to have the forecasting relations in the form of alinement-charts. The alinement-chart for a May 1 forecast of natural runoff of the Rio Grande above Del Norte, reproduced in Figure 6, is so designed that

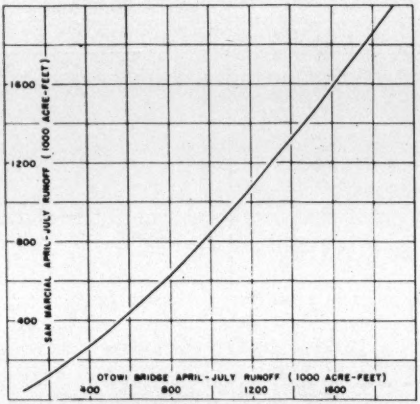


Fig. 5--Otowi Bridge - San Marcial runoff-relation

station-precipitation can be used, thus avoiding the need for computing weighted values. Separate alinement-charts could be constructed for each type of forecast in each of the tributary-basins.

Reliability and effectiveness of forecasts

There are a number of recognized measures of the reliability of a forecast. The most commonly used of these are the correlation-coefficient, average error, probable error, and standard error. When these evaluations are computed from forecasts based on data not included in the development of the procedure, they constitute a true measure of verification. If they are computed from data used in the analysis, they merely indicate the verification to be expected. The degree of uncertainty attached to a correlation-coefficient, or any other measure of reliability, is inversely related to the number of observations used in the correlation. The graph of yearly values of seasonal runoff shown in Figure 7 for the Rio Grande above Del Norte indicates the agreement between the observed amounts and the amounts estimated from the forecasting chart. The correlation-coefficients based on this period of record for April 1 and May 1 forecasts are 0.76 and 0.90, respectively. It may reasonably be assumed that forecasts for subsequent years will have substantially the same degree of reliability.

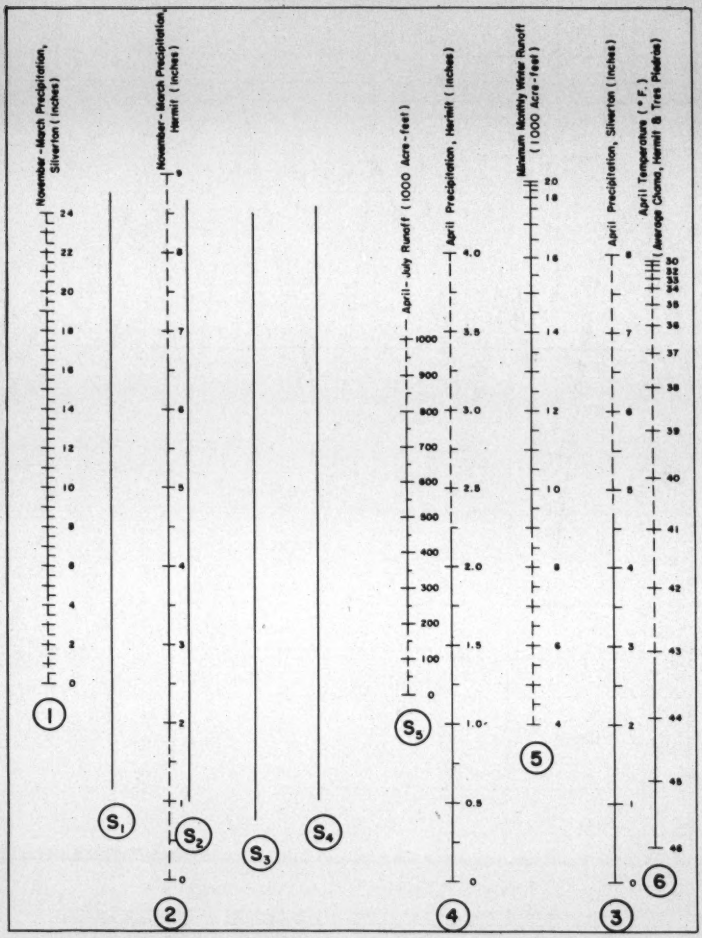


Fig. 6--Alinement chart, May 1, forecast, Rio Grande near Del Norte

The correlation-coefficient and the average error in per cent of normal for each basin studied are listed in Table 5. It is evident that seasonal runoff in the three western headwater-basins can be forecasted with the greatest degree of accuracy. These three basins are by far the most important runoff-producing areas. Greater degrees of error occur for the eastern headwater-basins and downstream-gages where the fluctuations in spring flow are most pronounced and where diversions represent a considerably greater proportion of total yield.

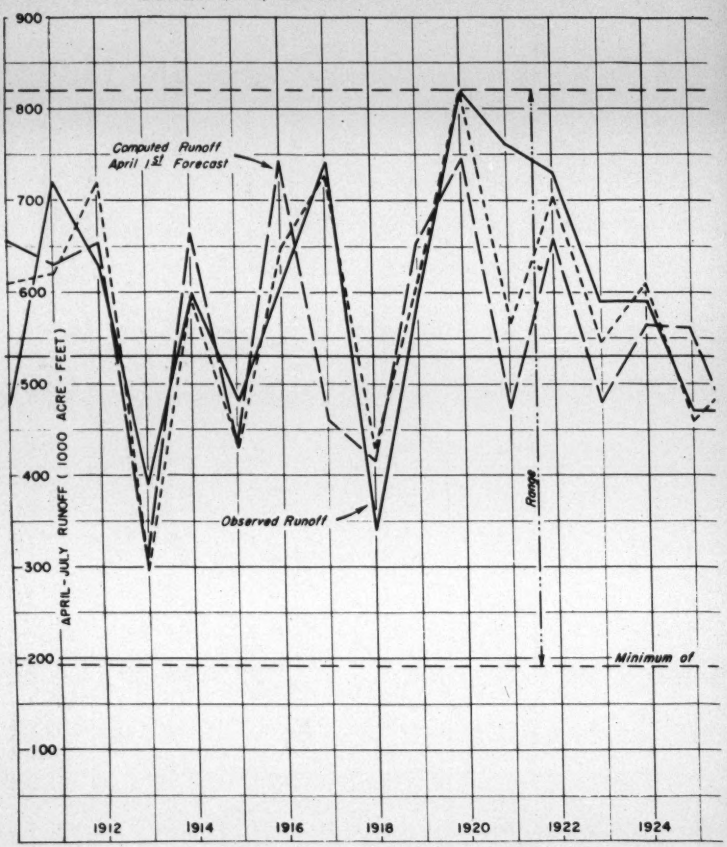
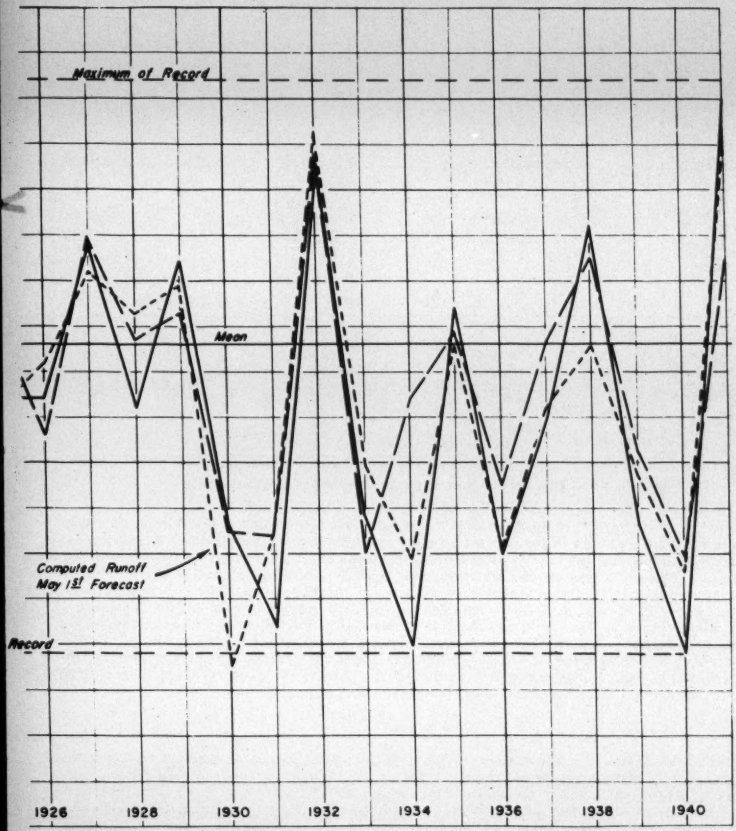


Fig. 7--Computed and observed

Table 5--Reliability of forecasting relations

Basin	Number of years used	Correlation-coefficient		Average error in per cent of normal	
		April 1	May 1	April 1	May 1
Rio Grande near Del Norte	32	0.76	0.90	17	11
Conejos River at Mogote	32	0.72	0.90	19	11
Rio Chama at Park View	20	0.88	0.91	17	14
Rio Colorado near Questa	28	0.56	0.74	35	24
Rio Taos at Los Cordovas	27	0.77	0.85	40	28
Rio Grande at Otowi Bridge	32	0.74	0.90	27	17
Rio Grande at San Marcial	32	0.66	0.86	36	27



runoff, Rio Grande above Del Norte

The effectiveness of a forecasting procedure depends not only on the degree of correlation, but also on the variability of the phenomenon to be forecast. If runoff is fairly stable from year to year, a forecast of normal every year would yield a small average error in per cent of normal. On the other hand, violent fluctuations of seasonal runoff would produce a large average error in per cent of normal. Hence, average error is not a true indication of the effectiveness of a forecasting relation. A method of determining the effectiveness used by the State Hydrometeorological Institute of the U.S.S R. [14] is illustrated in Figure 8. All errors are expressed as a per cent of the extreme range of the forecast-variable. In preparing a verification-graph for seasonal forecasting, the number of occurrences of deviations from normal of various magnitudes are first determined. From these data, a curve is plotted (Curve A, Fig. 8), which indicates the probability that a deviation of a given magnitude will not be exceeded. In other words, this curve gives verification-values of a hypothetical forecast of normal flow each year.

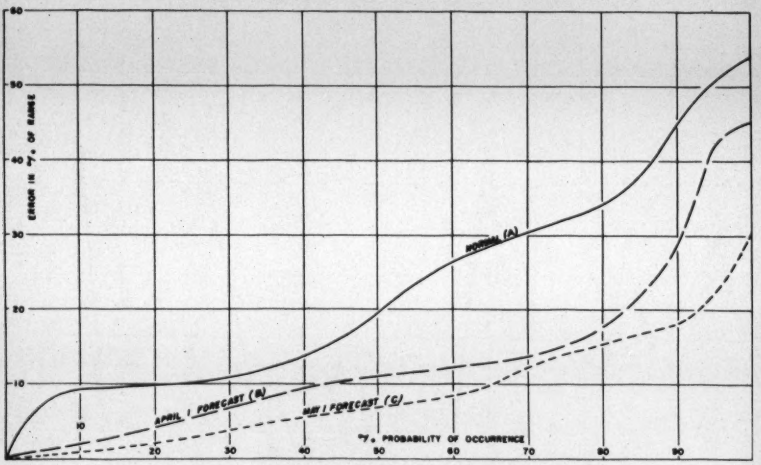


Fig. 8--Effectiveness of forecasts, Rio Grande above Del Norte

Curves B and C of Figure 8 are prepared in the same manner as Curve A and represent the verification of April 1 and May 1 forecasts computed from the forecasting-charts. The areas between Curves B and A, and between Curves C and A are indices to the effectiveness of the respective forecasts. Since this type of index is developed in per cent of range it may be used to compare forecast-procedures for widely separated basins of divergent characteristics. In Figure 8, the example shown is for the Rio Grande near Del Norte. Both the April 1 and May 1 forecast-curves have been plotted. The use of the chart is illustrated by the following example: Assume the adopted standard of acceptability to be a permissible error of 20 per cent in terms of range for four out of five forecasts (80 per cent probability). Enter the graph at 80 per cent probability of occurrence. The values of error read from the April 1 and May 1 curves are both less than 20 per cent, indicating that these forecasts meet the established standard.

Conclusions

A principal advantage in the statistical method for developing forecasting relationships is that procedures can be standardized for all regions within a forecasting-service. Modification as to the number or type of variables in the particular case are obviously necessary if characteristics of basin or region are to be taken into account. The period of winter precipitation and spring runoff will naturally differ between basins. In northern regions the snow-storage season may extend from October to April and the active melting-period from May to August. In relatively impervious areas, soil-priming may be unimportant so that the winter runoff or fall precipitation become insensitive as indices to runoff-losses.

As discussed previously, based on statistical analysis of past data, the probable effectiveness of an individual forecast or forecast-method can be determined. Also, certain limits of error can be established, and the probability of verification of future forecasts within these limits estimated.

Certain possibilities for refinement in procedure are immediately apparent. A sub-seasonal breakdown of data of precipitation and temperature will probably improve the correlations. It is reasonable to suppose that late winter snowfall is more effective than early snowfall, and to account for this effect would necessitate the separation of winter precipitation into two or more components. Another possibility is the use of a variable accumulation-period for winter precipitation. In some years, the beginning of snow-accumulation may be abnormally early or late. The selection of an arbitrary period of constant length may then exclude significant snowfall prior to the assumed initial date or include rainfall that has little effect on subsequent spring flow. To obviate this defi-

ciency it would be necessary to examine each season in detail and decide on an effective precipitation-total in each case.

Future possibilities of the statistical method include the expansion of the procedure to the forecasting of maximum discharge in spring, the distribution of runoff in the spring, and the extension of the time-range of forecasts. It is well known that a close correlation exists between peak snow-melt runoff and seasonal runoff-volume in high mountainous areas. This indicates that a seasonal runoff-forecast prior to the melting-season can be associated with a prediction of the probable peak-discharge to be reached during the melting-season. However, a more detailed study may indicate that other factors exercise important influences. For instance, while abnormally cold weather in the early melting-period may not influence the total amount of runoff, this delay in the runoff-release may allow snow to remain at extremely low elevations during the later warm spells and consequently produce an abnormal peak-discharge.

The time-range of forecasts may conceivably be extended so that from early reports of winter precipitation or other factors, tentative values of runoff can be predicted before April 1. The accuracy of such a forecast would depend on the proportion of the total winter precipitation which had occurred prior to the time of the forecast. As an example, suppose that in a certain region most of the precipitation normally occurs before February 1. Under these circumstances the snow-cover is almost fully developed on that date, and forecasts made then would approach the dependability of predictions issued two months later.

Acknowledgments

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Washington, D. C.

DISCUSSION

W. B. LANGBEIN (U. S. Geological Survey, Washington, D. C.)--The authors are to be complimented for having derived satisfactory forecasting-procedures that cut through the complexities of the snow-melt-runoff relation by the simple expedient of treating observations of precipitation

and temperature as relative indices of the active factors. Though simple, the analysis is a bold step that seeks to make efficient use of the available data by semi-graphical methods of correlation.

Statistical methods will probably be used increasingly in hydrology. The growing number of data require systematic organization and manipulation in accordance with known hydrologic principles. Statistics provide the philosophy and tools to this end. The results of this kind of analysis can be approximately appraised only by the accuracy with which it works. Comparisons with the record to date provide one test, time will furnish another and also indicate possible methods of improvements. If a satisfactory working correlation, consistent with the accuracy of the base-data, has been attained, arguments as to theory are inappropriate. A discussion of this paper can therefore only look toward suggestions of methods of improving the correlations.

(1) In computing the multiple correlation the question is raised whether the deviations from the preliminary regression should be expressed as percentages of runoff or quantitatively in acre-feet. It is perhaps worth investigating whether the effect of April temperature or minimum monthly runoff should be expressed as percentage.

(2) Would the error of estimate of the forecast of May 1 be diminished if consideration were given to the discharge during April in relation to April temperature? In other words, would the runoff-degree-day relation during April provide an additional clue to the volume of the snowpack? The method of analysis used seems sufficiently flexible to accommodate any number of variables.

(3) Possibly some of the deviations from the forecast-relationships may be due to conditions during the melting-season. Although such conditions are unknown at the time the forecast is made, it might be desirable to set up limits within which runoff might vary on that account. A forecast of the lowest possible runoff under the most adverse conditions might have special usefulness.

(4) The graphical presentation of the distribution of the errors of estimate is a unique and valuable feature. The errors are given as a per cent of range; the range depends on two items only. The errors might better be expressed in per cent of standard error or of the mean error, which reflect all of the values and hence are more stable.

The correlation-coefficient is frequently given with the intent of summarizing the accuracy of the correlation. The result is frequently misleading. Correlation-coefficients of 0.90 or better sometimes are associated with prohibitive mean or standard errors of estimate. Perhaps the ratio between the standard errors of estimate and the standard deviation of the dependent variable would furnish a more satisfactory guide to relative accuracy of the correlation.

VISIT OF THE SOVIET HYDROMETEOROLOGICAL MISSION, FEBRUARY 15 TO APRIL 30, 1943

Merrill Bernard

American hydrologists were favored with a visit by the Soviet Hydrometeorological Mission which included Major M. LVOVICH, Doctor of Geographical Sciences, representing the hydrologic interests of the Soviet Union.

It was the writer's privilege to assist in the arrangements under which Major Lvovich was given the opportunity to visit the Federal agencies interested in hydrologic matters, including the Geological Survey, Corps of Engineers, Forest Service, Federal Power Commission, Soil Conservation Service, National Resources Planning Board, Reclamation Bureau, Carnegie Institution of Washington (Department of Terrestrial Magnetism), and the Weather Bureau.

Field-visits included: The operational area of the Tennessee Valley Authority; the Coshocton (Ohio) Research Center of the Soil Conservation Service; the Koweeta (North Carolina) Research Project of the Forest Service; the Los Angeles District Engineer Office, Corps of Engineers; and the All-American Canal, Bureau of Reclamation.

A striking feature of the Mission's visit was the detail in which the Soviet scientists had organized the utilization of their time. Major Lvovich had an unusually extensive knowledge of the work and accomplishments of American hydrologists, permitting him to direct discussion quickly into productive channels.

The "International language" of science made it possible for members of the Mission, even within their comparatively short stay in the United States, to lay the beginning of many personal friendships. The war's end will find a substantial footing upon which to build a strong and permanent future for Soviet-American relations in the field of hydrometeorology.

U S. Weather Bureau,
Washington, D. C.

HYDROLOGY IN THE UNION OF SOVIET SOCIALIST REPUBLICS

Major M. Lvovich

Introduction

The first steps in the development of the modern hydrological observations in Russia are dated back to the seventies of the last century, when within the Department of Railroads and Communications a Committee on Navigation Survey was organized for conducting water-level observations on the navigable rivers. The water-measuring network in the eighties of the last century consisted of some hundred water-gaging points, where systematic observations were made of the water-levels and ice-conditions in rivers and lakes. The results of these observations have been periodically published in the form of "Water-level information" since the year 1880.

Before the first World War of 1914 in Russia there were also developed some works to satisfy the needs of the agricultural field. The Division of Land Improvement, organized within the Department of Agriculture, included a special Hydrometrical Section which established a small network of gaging-stations on minor rivers. This network proved to be an effective addition to the hydrographical network on large, and especially, navigable rivers.

A particularly active work was undertaken by the Hydrometrical Section of the Turkestan Region, established in the year 1910. There the development of irrigation had set some important tasks which differed from those directed towards the fulfilment of navigational aims. It proved necessary to determine the water-discharge on the rivers for computing the runoff needed in the calculation of irrigation-water resources. In this period, and for the first time in its history, the widely developed measures were started for determining the rate of water-reservoir silting. These activities of the Hydrometric Section exerted a considerable influence on the general development of hydrology in the Union of Soviet Socialist Republics. They made it necessary to create a methodical basis for the widely spread development of hydrological observations and investigations in the time to come.

In 1919, on the initiative of the Academy of Sciences of the Union of Soviet Socialist Republics, the Soviet Government decreed to establish the State Hydrological Institute. This Institute, being an All-Union Institution, had to tackle the tasks of many-sided investigations of the waters throughout the whole country as well as the reestablishment of hydrological works in the Union of Soviet Socialist Republics which were discontinued during the first World War and Civil Wars. These efforts are now directed wholly to the fulfilment of the demands of the economical building up of the young Soviet State.

The State Hydrological Institute is comprised of all the branches of hydrology, namely: River-hydrology; limnology; oceanology; underground-waters hydrology; water-regime of swamps; problems of hydrometry; hydrophysics; hydrodynamics; questions of washing of river-beds; et cetera. The most eminent scientists of the Union of Soviet Socialist Republics participated in the development of the new Institute, which from the very first moment of its activities developed a program of investigational works and created an extensive school of hydrologists. This Institute became a center in which was concentrated all the local hydrological work. It was also entrusted with the leading role in the planning of hydrological investigations and explorations. Systematic publications of scientific and applied literature in the field of hydrology were also started. In the meantime the Institute took the initiative in promoting the development of specialized higher hydrological education in the Union of Soviet Socialist Republics.

The general activities of the Institute have been determined by wide demands put on hydrology by the reconstruction of the national economy and by the rapid development of the industrial building. The shortest possible time was allowed for gathering hydrological data necessary for the calculations and other purposes of design. For this reason the Soviet hydrological science at the very beginning had to give up all attempts for pure hydrometrical investigations in connection with its

water-projects and had to follow the path of using the physical analysis of hydrological regimes and geographical generalizations. This course was followed by the State Hydrological Institute and most closely describes the path along which hydrological science in the Union of Soviet Socialist Republics has developed. We must remember that in the United States of America the network of gaging-stations 15 or 20 years ago was both relatively and absolutely much more extensive than in the Union of Soviet Socialist Republics. Nevertheless, due to vast territory, numerous water-projects, and variation in hydrological regimes, that network was unable to provide the answer to problems of water-economy on the basis only of observed hydrometrical factors without resorting to geographical generalizations.

In 1929 a Governmental decree created the Central Office of Hydrometeorological Service of the Union of Soviet Socialist Republics. This office concentrated all the hydrological and meteorological works conducted in the Union of Soviet Socialist Republics and became an operative hydrometeorological center for all the country. The State Hydrological Institute was incorporated into this office as a central scientific research institution.

In accordance with the decree of the Government of the Union of Soviet Socialist Republics, all the hydrometeorological stations controlled by the establishments of river-navigation, railway-transportation, and divisions of the People's Commissariat of Agriculture, et cetera, since 1930, were united in the Central Office of Hydrometeorological Service. The above-mentioned office was entrusted with giving meteorological messages for all purposes in connection with the national defense of the country, aviation, transport, power-economy, and agriculture. The Central Office of the Hydrometeorological Service set up a number of local offices controlling the hydrometeorological work carried out in different regions of the Soviet Union.

The network of hydrometeorological stations

The hydrometeorological network of the Union of Soviet Socialist Republics to January 1, 1941, consisted of 4,644 stations, including 3,362 basic stations controlled by the Central Office of Hydrometeorological Service and 1,282 temporary hydrological stations under various departments for satisfying the particular needs of a number of construction-projects. This number does not include gaging-stations functioning on the navigation-canals and in the power-plants and irrigation-systems.

While considering the development of the network of the permanent hydrological stations we get the following picture: In 1917 there were 1,508 stations; in 1927, 2,000 stations; in 1931, 3,000 stations; in 1935, 3,600 stations; and in 1940, 4,641 stations.

On the average, in all the territory of the Union of Soviet Socialist Republics, there is one hydrological station for each 4,524 square kilometers and in the European part of the Union of Soviet Socialist Republics one station per 2,000 square kilometers. The density of gaging-stations in the United States is about one station per 1,800 square kilometers. The character of the hydrological stations of the basic network are subdivided into the following groups: River hydrological stations of the first class, 11, of the second class, 229, of the third class, 1,410, and of the fourth class, 1,536; lake hydrological stations of the third class, 12, and of the fourth class, 151; runoff hydrological stations, 10; special evaporation-stations, 3 (except 36 evaporation-plants at the river hydrological stations of the second class).

This division of hydrological stations into classes is determined by the nature of the activities served by them. The first class comprises non-standard stations, carrying out their works according to individual programs which have pronounced scientific research-characteristics. They are highly specialized; some of them have as their main task the investigation of washing river-beds; others concentrate their efforts on the study of bottom and suspended river-sediments.

The stations of the second class, in addition to taking water-measuring observations, engage in computation of water-discharges, sediments, etc. These are set up with a permanent staff of hydrologist-engineers and technicians who supervise and control the work at the stations of the lower classes attached to stations of the second class. Hence, apart from performing their observational functions, the stations of the second class can be considered as small local hydrological centers.

At stations of the third class, observations are made of water-level, water-temperature, ice-conditions, and ice-thickness. The engineers and technicians at the stations of the second class systematically visit the stations of the third class (6 to 12 times yearly) for measuring water-discharges and those of suspended sediments.

The stations of the fourth class differ from the previous ones in that they do not take any measurements of water-discharges and sediments.

The observations made at the hydrological stations are standardized and are carried out in accordance with the "Instructions for the river hydrological stations", published in 1938. At the present time a new and enlarged edition of the instructions is in preparation.

All the resulting data of hydrological observations are sent to the stations of the second class where they are tabulated and organized, after which they are dispatched to the appropriate regional Hydrometeorological Division. Here the necessary procedures of controlling, elaborating, computing, and analyzing the daily water-discharges are conducted. All the materials pertaining to the hydrological observations are prepared by the Regional Divisions for publication in the form of "Hydrological annuals" which are combined into the "Water Cadasters" (see below). These publications include all the data of hydrological observations up to the year 1935.

More than 1,500 hydrological stations are included in the number of reporting stations which daily communicate the results of eight-hour observations by telegraph, telephone, or wireless.

The runoff-stations of the Union of Soviet Socialist Republics, conducting investigations of the formation of river-runoff, began their development not long before the present war. Small river-basins and artificial runoff-plots were established as research-projects.

The Central Methodic Runoff Station, located on the Valday Heights, is investigating the runoff-phenomenon and its controlling factors (precipitation, snow-cover, soil-moisture, frozen soil, evaporation, etc.) on the 14 natural small catchment-areas from two to 50 hectares in area as well as on 15 artificial plots ranging from 200 to 2,000 square meters in area. These observations are being conducted from the surface-runoff from slopes of different steepness. The influence exerted by land-tilling and forests on the runoff is also being carefully studied. Approximately the same program is adopted for the secondary runoff-stations. Certain runoff-stations investigate the processes of mud-flow floods (in the Alma-Ata District), others study the formation of runoff under conditions of perpetually frozen soil (Eastern Siberia). Still other stations are engaged in the investigation of the deformation of river-beds where systematic surveys of the river-beds on selected sections are made. One of the indicated stations is on the river of Amy-Darya, which has a bed considered to be the most changeable in the world. Special evaporation-stations and a number of river hydrologic stations are equipped with evaporation-tanks three meters in diameter.

In 1941, among the measures taken to unify the Services in connection with the conditions of the present war, an amalgamation of both the hydrologic and meteorological stations was put into effect. Further plans are directed towards the creation of a unified hydrometeorological network for which purpose special instructions are being compiled and special training and instruction given to collaborating workers.

The "Water Cadaster"

Not long before the present war the extensive and fundamental project of compiling and publishing the "Water Cadaster" for the Union of Soviet Socialist Republics was completed. The work occupied about ten years. The Cadaster contains all the materials of hydrological observations made on the rivers, lakes, and seas for the period from the beginning of the observations to 1935. This monumental edition must be regarded as a basic reference-book on hydrology in the Union of Soviet Socialist Republics and is being widely used for designing hydraulic works as well as in operational problems and for scientific hydrometeorological investigations. The "Cadaster" is considered to have created a new epoch in the development of the Soviet hydrology, as it makes available all hydrological materials for wide scale use and dissemination. Moreover, the work of compilation of the "Cadaster" gave a strong impetus to the education of a highly skilled staff of specialists who became available for the solution of hydrological problems brought forward by the present war.

The Hydrological Forecasting-Service

In the course of the last few years the Hydrological Forecasting-Service in the Union of Soviet Socialist Republics has experienced an intensive development. Every year the Forecasting-Service issues about 65,000 forecasts for the following factors affecting the regime of the rivers and lakes:

(1) Time of the opening of the rivers and lakes from ice
(2) Time of the freezing of rivers and lakes (the beginning of ice-drifting and ice-covering periods)
(3) Spring snow-floods (time of beginning, maximum discharge, volume, etc.)
(4) Mean monthly levels and discharges on the rivers for the navigation-periods
(5) The water-levels in ice-drifting periods
(6) Mean ten- and five-day water-levels and discharges on the rivers
(7) Summer rain-floods
(8) Daily water-levels on rivers in the period of the open channel
(9) The ice-depth on rivers and lakes

The operative forecasts of the hydrologic regime are given both by the central and district divisions of the hydrometeorological service. In the central divisions there are prepared, mainly, the so-called background forecasts of seasonal hydrological phenomena. These forecasts are given in the form of territorial generalizations and are used both for immediate operative purposes and as a basis or a background for compiling local (that is, for different points) forecasts by the district divisions. Thus the background forecasts of the opening and freezing periods of the rivers are presented in the form of maps showing the expected isochrones of the beginning of the ice-drifting period as well as of the ice-covering period.

The background forecasts of snow-flood volume and mean monthly discharges are given in the form of maps of isolines representing the "modal coefficients" (ratio of discharge of the given year to its modal value).

The form in which local forecasts are given is predetermined by a special "instruction for the issue, censure, and estimation of hydrological forecasts". It is considered obligatory that the values to be forecast are given within a specified range. For example, the expected water-discharges are from 100 to 120 cubic meters per second, the anticipated dates for the river-freezing are from November 8 to 16, etc. At the same time the range of magnitude cannot exceed ten per cent of the maximum range for the period of record.

The operative forms for the issuing of forecasts of seasonal hydrological phenomena contain information on the magnitude and the dates of the given phenomenon in the previous year as well as for the period of many years (low, mean, and high values). These data enable every interested person to determine the character of the anticipated phenomenon in comparison with the previous year and with the data taken for the period of record. To show the accuracy of the given forecast the form also indicates the so-called probability of verification.

In accordance with the rules adopted by the Hydrometeorological Service of the Union of Soviet Socialist Republics, the operative hydrological forecasts must comply with the following requirements:

(1) The forecasts must be given with the indication of the time of occurrence of the anticipated phenomenon.
(2) The forecast must indicate the magnitude of the expected phenomenon with the expected accuracy as a percentage of maximum range established by the period of record.
(3) The forecast must be given in compliance with the actual hydrometeorologic conditions existing at the time, as well as those existing before the forecasted phenomenon occurs.

Because of the above requirements there are not to be found in the Forecasting-Service of the Union of Soviet Socialist Republics any purely statistical methods of forecasting based only on the analysis of one-number series of a given phenomenon without supporting physical analysis. The most important results of the methodical investigations in the line of hydrological forecasting are published in the "Proceedings of the State Hydrological Institute" as well as in the "Proceedings of the Research Institutions of the Hydrometeorological Service of the Union of Soviet Socialist Republics."

The methods employed for forecasting the opening and freezing of rivers and lakes are largely dependent on the existing connection of these regime elements with the preceding hydrometeorological conditions.

The snow-cover is considered to be the main factor in determining the magnitude of spring snow-floods. In computing the forecasts of the spring floods both soil-moisture and frozen-soil conditions are taken into consideration. The intensity of snow-cover melting is also estimated. For the forecasting of the spring flood-processes in the Union of Soviet Socialist Republics we use

the principle of unit-graph method proposed by the American hydrologists. When used for estimating the snow-flood, this principle, though modified, gives fine results which can be regarded as an additional proof to the validity of SHERMAN'S idea which found its application in the forecasting of spring floods, too.

In connection with the forecasting of spring floods much attention is paid to the observations made of the snow-covering. The said observations, especially those of the depth and density of snow-covering, are conducted on special plots, located near the hydrometeorological stations. Some of these stations possess three such plots, one of them being a field-plot and the two others wooded ones, located among the trees and in the forest glades.

In the high mountainous regions, Middle Asia and the Caucasus, the snow-measuring surveys are being systematically conducted for forecasting spring-summer floods. These works are quite similar to those conducted in the Western States of the United States of America. For forecasting low-water and rain-flood levels on the large rivers, we use the method of corresponding water-levels. For the small rivers the forecasts are given according to the unit-graph method, which for the past few years is being used more and more in the Union of Soviet Socialist Republics.

A new achievement in the field of giving forecasts, according to the method of corresponding water-levels, is the use of maps showing isochrons of the velocity of water running in river-channels (E. V. BERG).

The unit-graph method is applied for forecasting floods in the rivers with the drainage-areas less than 5,000 to 6,000 square kilometers and only in some cases for the greater rivers. This method, which no doubt will have bright prospects in time to come, may cause some difficulties in the beginning of its use in accounting for the precipitation-losses of infiltration. Nevertheless, if modified according to the conditions existing in the Union of Soviet Socialist Republics and improved in some respects, this unit-graph method may so far be considered as the only scientifically grounded method for forecasting rain-floods in small rivers.

The proper knowledge of probable errors in the given forecasts is considered to be quite obligatory in the Union of Soviet Socialist Republics. As the greatest permissible error in a forecast we assume the value amounting to 20 per cent of the maximum range of the seasonal hydrological phenomena, or 20 per cent of accounting range (change of water-levels within the period of the forecast) for the short-range forecasts. All the forecasts exceeding 20 per cent of their range are to be considered as unsatisfactory.

In cases when the error does not exceed 10 to 20 per cent of their ranges the forecasts are held to be satisfactory; with five to ten per cent of these errors they are good enough, and with the errors under five per cent of range they are marked "excellent".

The third criterion considered as necessary for determining the validity of the method of forecasting is termed the "effectiveness of the method". The mean verification of the forecasts of the seasonal hydrological phenomena (with the mean timeliness of about 40 to 50 days) is approximately 80 per cent, and that for the short-range forecasts (with the mean anticipation of three days) is up to 95 per cent. This means that four-fifths of the "long-range" operative forecasts are limited to errors that are less than the greatest permissible ones. As for the "short-range" forecasts, only five per cent of the whole number must be classified as unsatisfactory.

The research-work in the field of hydrology

A number of research-activities in the field of hydrology have been mentioned above in connection with the solution of some tasks of particular nature and character. However, rather extensive investigations of purely practical character have been accomplished. Among these works must be mentioned the investigations concerning the interchange of heat between water and air (heat interchange-evaporation), convection, and solar radiation. The investigations concerning the evaporation from the land-surface involving gradients of air-moisture in vertical and horizontal direction lead us much nearer the quantitative solution of this problem. The studies conducted by the Soviet hydrologist, S. I. RUDENKO, have been important in the solution of the problem concerning the quantitative estimation of the transpiration-capacity of forests.

The studies of the formation of internal water-ice (anchor-ice) started in the Union of Soviet Socialist Republics many years ago, are still in process of development at the present time. As a new feature we may mention the investigation concerning the "nidus", or the formation of internal water-ice under the influence of screw-circulation currents of the stream which are dependent on

the configuration of the river-bed (N. B. SOKOLNIKOFF).

Of the same interest are studies of the forms of crystals in anchor-ice (V. K. ALTBERG) and rate of ice-cover formation on the rivers. These investigations served as a basis for a proposed method for forecasting the ice-cover depth (G. R. BERGMAN and V. V. PIOTROVICH).

Of great importance are the investigations started not long before the present war concerning the heat-balance in the snow-cover for melting. For this purpose the runoff-stations of the State Hydrological Institute made very elaborate observations which enabled us to solve, in terms of the first approximation, the equation of the heat-balance for snow-melting.

Theoretical investigations were also made of the limits for applying statistics and probability-theory in hydrology; particularly the work done by BROVKOVICH, who proposed a new method of probability and statistical analysis which has enabled us to establish a theoretical basis for evaluating the methods of forecasting and operative forecasts.

In the domain of investigating the washing of the river-bed and the movement of the river-sediments must be noted the works of M. A. VELIKANOFF, M. B. POTAPOFF, MAKAVEYEFF, LEVI, and GONCHAROFF, which resulted in verifying and confirming the theoretical basis for the problem in question.

Among the works concerning the geographical generalization of the hydrological regime are those of the writer which have made it possible to map the annual estimated runoff of the rivers of the world, as well as the classification of the water regime of rivers according to the sources of the water-supply and the distribution of the runoff through the seasons.

Hydrological education

As far back as the year 1922, the special education of hydrologists was conducted in the Railroads and Communications Institute in Leningrad and the Higher Technical Institute in Moscow. At the Higher Institute special courses on hydrology were given. The first of these courses was published in 1923, and must be considered as the first text-book on hydrology appearing in Russia.

In 1922 the first chair of hydrology was organized at the Geographical Faculty of the Leningrad University. Later on it was extended and reorganized into a Section of Hydrology. The Leningrad University was the first Higher School in the Union of Soviet Socialist Republics which began graduating hydrologists and providing them with a special diploma.

The preparation of hydrologists was greatly enlarged and in 1930 a special Hydrometeorological Institute was organized with a Hydrological Faculty as a constituent part. Besides these two Higher Schools, there exist five Hydrometeorological Technical Schools, preparing specialists in hydrology of middle qualification.

The special hydrological education at the Higher Schools begins from the second school-year and lasts for five years. The students are lectured on hydrometry, hydrochemistry, hydrography, general hydrology, potamology, limnology, oceanology, underground waters, and swamp-hydrology. The students are also given a course on hydrological forecasts. Training is given both in laboratories and in the field, including practical work at the stations of the Hydrometeorological Service and its affiliated institutions.

Hydrology and the present war

Immediately after the treacherous attack of the German fascist armies against the Soviet Union, the Soviet hydrologists, headed by the Hydrometeorological Service, turned their activities towards the many-sided questions of warfare. Many of our hydrologists entered the ranks of the Red Army and their activities both at the front and in the rear are providing every assistance to the hydrometeorological service of the war fronts.

A great work is being carried on in the rear of our country in connection with the enormous building up of war-works which were evacuated from the front-line region.

Naturally, the main task of the Soviet hydrologists, as of all the citizens of the Union of Soviet Socialist Republics, consists in their working and fighting against the German fascist armies for the complete liberation of our beloved Motherland.

Hydrometeorological Service of the Union of Soviet Socialist Republics,
Moscow, Union of Soviet Socialist Republics

Robert E. Horton

Table 1--Summary of evaporation-records, U. S. Weather Bureau Class-A pans

Station	No.	Long.	Lat.	Elev.	Years: From	Years: To	Years missing	Years used	Observed: Yr.	Observed: S	Observed: W	E_y/E_s	Observed & Estimated: Yr. (a)	Observed & Estimated: S	Observed & Estimated: W (a)	Base factor	Corrected to Base: Yr.	Corrected to Base: S	Corrected to Base: W
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)
Aberdeen, Idaho	1	112°-53'	42°-40'	4400	1935	1940	1	5		42.40		1.32	63.60	42.40	21.20	1.12	56.79	37.86	18.93
Agric. College (Bozeman) Mont.	2	111-02	45-45	4900	1917	1941	0	25		32.49		1.27	41.26	32.49	8.77	1.00[b]	41.26	32.49	8.77
Agric. College, N.M.	3	106-45	32-17	3863	1919	1941	1	22	90.98	60.17	30.81	1.51	90.98	60.17	30.81	.995	91.44	60.47	30.97
Alamogordo Dam, N.M.	4	106-23	34-36	4306	1939	1941	0	3	96.40	65.39	31.01	1.47	96.40	65.39	31.01	1.07	96.03	64.07	28.96
Alvarado, Calif.	5	122-07	37-33	5	1925	1941	1	16	53.50	37.65	15.85	1.41	53.50	37.65	15.85	.972	55.04	38.73	16.31
Ames, Iowa	6	93-39	42-02	1066	1935	1941	0	7		42.72		1.32	56.39	42.72	13.67	1.01	55.83	42.30	13.53
Arbon Rock, Idaho	7	116-15	43-30	3230	1916	1940	0	25		42.79		1.30	55.63	42.79	12.84	1.00[b]	55.63	42.79	12.84
Austin (Hill's Ranch), Tex.	39	97-44	30-17	605	1916	1941	1	25	65.36	43.78	21.58	1.49	65.36	43.78	21.58	1.00[b]	65.36	43.78	21.58
Bachus Ranch, Calif.	8	118-11	34-55	2620	1927	1941	1	4	120.28	91.12	29.16	1.32	120.28	91.12	29.16	.916	131.31	99.48	31.83
Bee Tree Dam, N.C.	9	82-26	35-39	2557	1935	1941	1	6	41.93	29.17	12.76	1.44	41.93	29.17	12.76	1.01	41.51	28.88	12.63
Boulder City, Nev.	10	114-44	36-00	2525	1936	1941	0	6		86.91		1.40	121.67	86.91	34.76	.973	125.05	89.31	35.74
Bridgeport, Nebr.	11	103-06	41-40	3658	1936	1941	1	4		50.75		1.33	67.50	50.75	16.75	1.03	65.54	49.27	16.27
Buffalo, N.Y.	12	78-53	42-53	604	1938	1941	1	3	43.82	27.79	16.03	1.61	43.82	27.79	16.03	1.05	41.71	26.45	15.26
Cahoe Brook, N.J.	140	74-15	40-15	180	1935	1941	0	7		23.77		1.34	31.85	23.77	8.08	1.04	30.62	22.85	7.77
Chapel Hill, N.C.	13	79-03	35-55	501	1921	1935	0	15	42.70	28.95	13.75	1.48	42.70	28.95	13.75	1.00[b]	42.70	28.95	13.75
Cherokee, Iowa	14	95-33	42-45	1196	1938	1941	0	4		41.11		1.32	54.27	41.11	13.16	.960	56.53	42.82	13.71
Chula Vista, Calif.	15	117-06	32-37	9	1919	1941	0	23	62.07	38.87	23.20	1.60	62.07	38.87	23.20	1.00[b]	62.07	38.87	23.20
Clarinda, Iowa	16	95-06	40-48	1004	1938	1941	0	4		47.35		1.34	63.45	47.35	16.10	.960	66.09	49.32	16.77
Clarksburg, W. Va.	17	80-21	39-17	1015	1923	1941	0	19		27.86		1.36	37.89	27.86	10.03	1.01	37.51	27.58	9.93
Clay City, Nev.	18	116-25	36-30	2185	1927	1936	2	8		98.78		1.34	134.34	98.78	35.56	1.01	133.01	97.79	35.22
Columbia, Mo., No. 1	19	92-20	38-57	737.5	1916	1927	0	12		27.57		1.38	38.05	27.57	10.48	1.05	36.22	26.24	9.98
Columbia, Mo., No. 2	20	92-20	38-57	748	1916	1926	0	11		36.52		1.38	50.40	36.52	13.88	1.04	48.48	35.13	13.35
Columbus (O.S.U.), Ohio	21	83-00	39-58	757	1920	1941	0	22		25.76		1.36	35.03	25.76	9.27	1.00[b]	35.03	25.76	9.27
Conchas Dam, N.M.	22	104-11	35-23	4265	1937	1941	0	5	101.91	69.19	32.72	1.47	101.91	69.19	32.72	1.10	92.65	62.90	29.75
Corvallis, Oreg.	23	123-18	44-34	266	1932	1941	0	10		29.03		1.29	37.65	29.03	8.62	1.02	36.70	28.45	8.25
Davis, Calif.	24	121-44	38-32	51	1934	1941	0	8	66.61	50.22	16.39	1.33	66.61	50.22	16.39	.935	71.24	53.71	17.53
Dayton, Ohio	25	84-12	39-46	741	1937	1941	0	5		32.46		1.36	44.15	32.46	11.69	1.04	42.42	31.19	11.23
Deer Flat, Idaho	26	116-45	43-35	2510	1916	1925	0	10		35.28		1.30	45.86	35.28	10.58	1.00[b]	45.86	35.28	10.58
Dickinson, N. D.	27	102-48	46-48	2543	1939	1941	0	3		32.28		1.26	40.67	32.28	8.39	.966	42.10	33.42	8.68
Dilley, Tex.	28	99-10	28-42	569	1928	1941	1	13	75.77	50.85	24.92	1.49	75.77	50.85	24.92	.999	76.15	50.90	25.25
Dobseland, Calif.	29	122-00	39-33	160	1919	1922	1	3	58.36	44.06	14.30	1.32	58.36	44.06	14.30	1.07	54.56	41.19	13.37
Eagle Nest, N.M.	30	105-15	36-34	8219	1937	1941	0	5		38.40		1.40	53.76	38.40	15.36	1.10	48.86	34.90	13.96
Elephant Butte Dam, N.M.	31	107-10	33-10	4265	1917	1941	0	25	100.18	67.53	32.65	1.48	100.18	67.53	32.65	1.00[b]	100.18	67.53	32.65
El Vado Dam, N.M.	32	106-44	36-37	6424	1937	1941	1	4		46.35		1.40	64.89	46.35	18.54	1.10	58.98	42.12	16.86
Experiment, Ga.	133	84-15	33-15	946	1937	1941	0	5		38.97		1.45	56.51	38.97	17.54	.995	56.79	39.26	17.53
Fairhope, Ala.	134	87-50	30-30	150	1939	1941	1	3	49.03	31.99	17.04	1.53	49.03	31.99	17.04	1.01	48.54	31.67	16.87

[a] Where only observations in summer, column (11), are available, year and winter are obtained from relation (E_y/E_s), per column (13), based on stations having records of complete years. [b] Base-stations.

Evaporation-data, Class-A stations.--The monthly and annual numbers of Climatological Data of the United States contain monthly evaporation-data at United States Weather Bureau Class-A evaporation-stations. A four-foot diameter circular evaporation-pan ten inches deep is used. The pan stands on a wooden grillage with the rim about 14 inches above ground. Water is maintained at a depth of one to two inches below the rim of the pan. These records were compiled for over

Table 1--Summary of evaporation-records, U. S. Weather Bureau Class-A pans--Continued

Station	No.	Long.	Lat.	Elev.	Years: From	Years: To	Years: Missing	Years: Used	Observed: Yr.	Observed: S	Observed: W.	E_W/E_S	Observed & Estimated: Yr. (a)	Observed & Estimated: S	Observed & Estimated: W (a)	Base Factor	Corrected to Base: Yr.	Corrected to Base: S	Corrected to Base: W
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)
Fallon, Nev.	33	118-42'	39-26'	3965	1938	1941	0	4		38.27		1.36	52.05	38.27	13.78	.962	54.11	39.78	14.33
Fall River Mills, Calif.	34	121-26	41-01	3340	1926	1941	12	3	66.40	52.54	13.86	1.26	66.40	52.54	13.86	.970	68.45	54.16	14.29
Fort Collins, Colo.	35	105-05	40-35	4985	1938	1941	0	4		34.31		1.24	45.98	34.31	11.67	.891	51.61	38.51	13.10
Fort Peck, Mont.	36	106-24	48-00	2280	1935	1941	6	7		48.85		1.22	59.60	48.85	10.75	1.04	57.34	47.00	10.34
Gardiner, Me.	37	69-45	44-15	163	1916	1924	0	9		25.29		1.29	32.62	25.29	7.33	.970	33.63	26.07	7.56
Germfask, Mich.	136	86-00	46-15		1939	1941	0	3		27.59		1.26	34.76	27.59	7.17	1.10	31.60	25.08	6.52
Hackberry, La.	130	93-21	30-00	5	1939	1941	0	3	61.96	43.94	18.02	1.41	61.96	43.94	18.02	.980	63.22	44.83	18.39
Hays, Kans.	38	99-20	38-51	2000	1938	1941	0	4		74.64		1.38	103.00	74.64	28.36	.891	115.60	83.77	31.83
Hope (Exptl. Farm), Ark.	40	93-33	33-37	375	1937	1941	0	5	63.92	42.78	21.14	1.49	63.92	42.78	21.14	.991	64.50	43.17	21.33
Indianapolis, Ind.	135	86-12	39-45	718	1937	1941	0	5		35.10		1.36	47.74	35.10	12.64	1.04	45.94	33.75	12.19
Iowa City, Iowa	41	91-29	41-41	780	1938	194	0	4		26.07		1.33	47.97	36.07	11.90	.960	48.97	37.57	12.40
Iron Forks Expt. Forest (near Alger)	127	98-20	34-40	1385	1939	1941	0	3	36.80	24.86	11.96	1.48	36.80	24.86	11.94	.966	38.09	25.73	12.36
Ithaca, N.Y.	42	76-29	42-27	890	1919	1941	15	8		28.48		1.32	37.61	28.48	9.13	1.00 [b]	37.61	28.48	9.13
Jerome, Idaho	43	115-00	43-00	3893	1919	1927	0	9		36.97		1.30	48.06	36.97	11.09	1.03	46.47	35.90	10.77
Keystone Dam, Nebr.	44	101-39	41-13	3170	1938	1941	1	3		52.40		1.33	69.69	52.40	17.29	.960	72.59	54.58	18.01
Lake Kachess, Wash.	137	121-20	47-25	2270	1935	1941	1	6		26.26		1.24	32.56	26.26	6.30	1.05	31.01	25.01	6.00
Lakeside (Osage Dam), Mo.	143	92-38	38-12	595	1935	1941	0	7	56.22	40.66	15.56	1.38	56.22	40.66	15.56	1.01	55.71	40.25	15.46
Lamoille, Nev.	45	115-30	40-45	6100	1918	1941	4	21		42.42		1.34	56.84	42.42	14.42	1.00 [b]	56.84	42.42	14.42
Lawton, Okla.	46	98-25	34-33	1111	1937	1941	1	4		50.84		1.43	72.77	50.89	21.88	.918	78.27	53.43	23.84
Lee's Ferry, Ariz.	47	111-35	36-50	3143	1922	1937	9	7	91.70	67.04	24.66	1.37	91.70	67.04	24.66	.969	94.63	69.18	25.45
Lifton, Idaho	48	111-15	42-10	5926	1935	1940	0	6		42.85		1.32	56.56	42.85	13.71	1.12	50.50	38.26	12.24
Lincoln, Nebr.	49	96-45	40-49	1109	1919	1941	1	22		48.59		1.34	65.11	48.59	16.52	1.00 [b]	65.11	48.59	16.52
Lodi, Calif.	50	121-16	38-08	50	1932	1941	0	10	70.31	55.00	15.31	1.28	70.31	55.00	15.31	.979	74.88	58.57	16.31
Malta, Mont.	51	107-45	48-22	2255	1926	1941	1	15		41.55		1.22	50.69	41.55	9.14	1.04	48.76	39.97	8.79
Mandan, N.D.	52	100-54	46-48	1750	1939	1941	0	3		32.13		1.26	40.48	32.13	8.35	.966	41.91	33.26	8.65
Manhattan, Kans.	53	96-35	39-12	1100	1925	1941	8	9		49.21		1.36	66.93	49.21	17.72	1.02	65.58	48.22	17.36
Marshfield, Wis.	131	90-13	44-42	1250	1940	1941	0	2		36.58		1.50	45.87	30.58	15.29	1.08	42.47	28.31	14.16
Medford Expt'l. Sta., Oreg.	54	122-52	42-23	1457	1938	1941	0	4		40.17		1.32	53.02	40.17	12.85	.964	55.00	41.67	13.33
Mesa Expt'l. Farm, Ariz.	55	111-48	33-25	1225	1917	1941	0	25	79.28	53.51	25.77	1.48	79.28	53.51	25.77	1.00 [b]	79.28	53.51	25.77
Midlake, Utah	56	112-25	41-10	4235	1925	1928	0	4		65.98		1.33	85.25	65.98	19.27	.976	83.86	57.61	26.25
Milner Dam, Idaho	57	114-00	42-30	4200	1927	1940	0	14		42.25		1.32	55.77	42.25	13.52	1.02	56.65	41.40	13.25
Montrose, Colo.	126	107-50	38-30	5811	1939	1941	0	3		41.75		1.38	63.18	45.75	17.39	.886	71.26	51.62	19.64
Moscow, Idaho	129	117-00	46-42	2628	1939	1941	0	3		29.65		1.26	37.36	29.65	7.71	.964	38.75	30.76	8.00
Murphy, N.C.	58	84-02	35-05	1575	1935	1941	0	7	42.01	29.76	12.25	1.41	42.01	29.76	12.25	1.01	41.59	29.46	12.13
Myton, Utah	59	109-50	40-15	5030	1933	1941	2	7		41.72		1.34	55.96	41.72	14.18	.997	56.07	41.84	14.23
Navajo Expt. Sta., N.M.	60	108-50	35-47	6455	1937	1941	0	5		61.78		1.42	87.73	61.78	25.95	1.10	78.74	56.15	23.59

100 stations having records varying from three to 25 years' duration. South of latitude 37° north, the records are mostly maintained throughout the entire year. For stations with full yearly records the means of the evaporation were separately determined for the six months of summer, May to October, the six months of winter, November to April, and also for the year. These original data, together with information regarding the stations, is given in columns (1) to (11), inclusive, of Table 1.

Evaporation-data, United States Bureau of Plant Industry stations--Table 2 contains, in columns (1) to (13), corresponding data for United States Bureau of Plant Industry stations (designated

Table 1--Summary of evaporation-records, U. S. Weather Bureau Class-A pans--Concluded

Station	No.	Long.	Lat.	Elev.	Years: From	Years: To	Years: Missing	Years: Used	Observed: Yr.	Observed: S	Observed: W	E_W/E_S	Observed, Estimated: Yr. (a)	Observed, Estimated: S	Observed, Estimated: W (a)	Base Factor	Corrected to Base: Yr.	Corrected to Base: S	Corrected to Base: W
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)
Norman (Okla. Univ.), Okla.	61	97°-25'	35-10	1171	1937	1941	0	5		46.75		1.42	46.38	46.75	19.63	.918	72.31	54.93	21.38
Norris, Tenn.	62	84-04	36-12	1000	1935	1941	0	7	42.34	30.78	11.56	1.37	42.34	30.78	11.56	1.01	61.92	30.47	11.45
Oakdale, Calif.	63	120-49	37-52	215	1919	1941	2	21	79.36	64.13	15.23	1.42	79.36	64.13	15.23	1.00[b]	79.36	64.13	15.23
Pickwick Landing, Tenn.	64	88-15	35-03	397	1936	1938	0	3	45.34	32.94	12.40	1.38	45.34	32.94	12.40	1.02	64.43	32.28	12.15
Piute Dam, Utah	65	111-50	38-20	5900	1919	1941	1	23		51.63		1.38	70.97	51.43	19.54	1.00[b]	70.97	51.43	19.54
Pleasantville, N. J.	161	74-10	39-25	8	1935	1941	0	7		32.49		1.36	44.19	32.49	11.70	1.04	62.49	31.24	11.25
Portales Expt. Sta., N. M.	66	103-40	34-15	4004	1934	1941	1	7	88.81	58.86	29.95	1.51	88.81	58.86	29.95	1.12	79.30	52.55	26.75
Provo, Utah	67	111-40	40-14	4532	1919	1926	0	8		33.66		1.34	45.10	33.66	11.44	1.01	44.65	33.32	11.33
Roosevelt, Ariz.	68	111-10	33-45	2175	1916	1941	1	25	78.81	57.42		1.37	78.81	57.42	21.39	1.00[b]	78.81	57.42	21.39
Runyon, N. J.	162	74-20	40-20	18	1935	1941	0	7		28.79		1.34	38.58	28.79	9.79	1.04	37.09	27.68	9.41
Russellville (Green Hussey), Ark.	69	93-06	35-18	526	1937	1941	0	5	57.81	40.68	17.13	1.42	57.81	40.68	17.13	.991	58.33	41.05	17.28
St. Louis (Washington), Mo.	128	90-19	38-38	536.5	1938	1941	0	4		35.09		1.38	48.42	35.09	13.33	.960	51.44	36.55	14.89
Salt Lake Airport, Utah	70	111.57	40-46	4227	1928	1933	1	5		60.00		1.24	80.40	60.00	20.40	.986	81.56	60.85	20.69
Santa Fe Field, N. M.	71	106-02	35-38	7013	1917	1933	2	15	66.82	46.97	17.85	1.38	66.82	46.97	17.85	.944	68.67	49.76	18.91
Savannah, Tenn.	164	88-16	35-13	430	1919	1941	0	3	45.02	32.70	12.32	1.38	45.02	32.70	12.32	1.02	64.12	32.05	12.07
Sierra Ancha, Ariz.	72			(5100)	1937	1941	0	5	71.66	51.31	20.35	1.40	71.66	51.31	20.35	1.03	69.58	49.82	19.76
Silverhill, Ala.	73	87-40	30-32	256	1920	1927	0	8	59.67	39.54	20.13	1.51	59.67	39.54	20.13	.975	61.20	40.55	20.65
Stuttgart (Rice Expt. Farm), Ark.	74	91-18	34-28	198	1929	1941	1	12	52.72	37.87	14.85	1.39	52.72	37.87	14.85	1.04	49.71	35.70	14.01
Tahoe, Calif.	138	120-10	39-10	6230	1935	1941	0	7		21.86		1.36	29.73	21.86	7.87	.925	32.14	23.63	8.51
Tifton, Ga.	134	83-31	31-26	370	1937	1941	0	5		37.19		1.49	55.41	37.19	18.22	.995	55.69	37.38	18.31
Tipton, Okla.	75	99-08	34-26	1355	1938	1941	1	3		62.50		1.43	89.38	62.50	26.88	.891	100.32	70.15	30.17
Tribune, Kans.	76	101-47	38-28	3612	1919	1941	0	23		61.74		1.38	85.20	61.74	23.46	1.00[b]	85.20	61.74	23.46
Tucson (Univ. Ariz.), Ariz.	77	111-00	32-12	2423	1932	1941	0	10	89.04	61.30	27.74	1.45	89.04	61.30	27.74	.952	93.53	64.39	29.14
Utah Lake (Clear), Utah	78	111-55	40-20	4497	1927	1941	0	15		53.03		1.34	71.06	53.03	18.03	.993	71.56	53.40	18.16
Valier, Mont.	79	112-40	48-20	3825	1917	1941	1	24		39.31		1.22	47.96	39.31	8.65	1.00[b]	47.96	39.31	8.65
Vicksburg, Miss.	132	90-50	32-17	234	1939	1941	0	3	50.77	35.84	14.93	1.42	50.77	35.84	14.93	1.02	49.77	35.13	14.64
Voorheesville, N. Y.	80	73-54	42-39	310	1917	1941	0	24		27.72		1.32	36.59	27.72	8.87	1.00[b]	36.59	27.72	8.87
Walla Walla, Wash.	81	118-22	46-03	1000	1916	1931	2	14		41.27		1.26	52.00	41.27	10.73	.985	52.79	41.90	10.89
Warmspring, Oreg.	82	121-15	44-26	3310	1928	1941	2	12		54.94		1.29	70.87	54.94	15.93	1.00[b]	70.87	54.94	15.93
Wichita, Kans.	83	97-16	37-38	1377	1919	1926	0	8		49.93		1.39	68.40	49.93	19.47	.954	72.75	52.33	20.42
Willcox, Ariz.	84	109-50	32-00	4190	1917	1935	7	12	88.69	54.91	33.78	1.62	88.69	54.91	33.78	1.00[b]	88.69	54.91	33.78
Willow Cr. Res. (Gilman), Mont.	85	112-21	45-50	4474	1925	1928	0	4		29.09		1.27	36.94	29.09	7.85	.890	41.51	32.68	8.83
Wind River, Wash.	144	122-00	45-50	1138	1935	1941	2	5		29.08		1.27	36.93	29.08	7.85	1.05	35.17	27.69	7.48
Wooster, Ohio	86	81-56	40-47	1030	1920	1941	1	21		26.50		1.34	35.51	26.50	9.01	1.00[b]	35.51	26.50	9.01
Yuma Citrus Sta. (Roth Mesa), Ariz.	87	114-36	32-45	190.3	1921	1941	0	21	118.68	80.91	37.77	1.47	118.68	80.91	37.77	.987	120.24	81.98	38.26
Yuma Evap. Sta., Ariz.-I	88	114.36	32-45	150	1917	1927	0	11	76.56	50.54	26.02	1.52	76.56	50.54	26.02	1.08	70.89	46.80	24.09
Yuma Evap. Sta., Ariz.-II					1932	1940	1	8	104.15	69.07	35.08	1.51	104.15	69.07	35.08	.918	113.45	75.24	38.21

Class-B stations), compiled from previous publications [see 1 of "References" at end of paper]. For many of these stations the records are maintained only during the six-month period, April to September. For stations with yearly records the evaporation for May to October and for November to April was determined and the original results, with accompanying data, are given in columns (1) to (13) of Table 2.

At Class-B stations a circular buried pan six feet in diameter (but originally eight feet in diameter at some stations) is used. The rim of the pan projects three inches above ground-level

Table 2--Summary of evaporation-records, Class-B stations

Station	No	Long.	Lat.	Elev.	Years From	Years To	Years Missing	Years Used	Size of Pan, Ft.	Pan Factor	Observed Yr.	Observed S April-Sept. Inch.	Observed W	E_y/E_s	Observed & Estimated Yr.	Observed & Estimated S	Observed & Estimated W	Class A Base Yr.	Class A Base S	Class A Base W
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)
Aberdeen, Idaho	1	112-53	42-40	4400	1912	1920		9	6	1.09		40.68		1.32	53.70	40.68	13.02	67.12	50.85	16.27
Akron, Colo	89	103-14	40-10	4650	1908	1915	1	7	8	"		42.57		1.34	57.04	42.57	14.47	71.30	53.21	18.09
" "					1916	1932		17	6	"		44.25		1.34	59.30	44.25	15.05	74.12	55.31	18.81
Amarillo, Tex.	90	101-50	35-13	3676	1907	1909		3	8	"		52.96		1.42	75.20	52.96	22.24	94.00	66.20	27.80
" "					1910	1919		10	6	"		51.86		1.42	73.64	51.86	21.78	92.05	64.83	27.22
Angleton, Tex.	112	95-24	29-09	23	1915	1932		18	6	"	44.69	29.26 [2]	15.43	1.53	44.69	29.26	15.43	55.86	36.58	19.28
Archer, Wyo.	91	104-35	41-10	6012	1913	1932		20	6	"		36.82		1.33	49.09	36.82	12.27	61.36	46.02	15.34
Ardmore, S.D.	92	103-35	43-20	3557	1913	1932		20	6	"		38.19		1.30	49.65	38.19	11.46	62.06	47.74	14.32
Baltimore, Tex.	123	103-00	31-00	3200	1916	1932		14	6	"	70.60	45.36 [2]	25.24	1.56	70.60	45.36	25.24	88.25	56.70	31.55
Beaumont, Tex.	113	94-00	30-00	28	1917	1932		16	6	"	46.80	29.91 [2]	16.89	1.57	46.80	29.91	16.89	58.50	37.39	21.11
Beeville, Tex.	117	97-38	28-32	240	1915	1932		18	6	"	59.06	38.47 [2]	20.39	1.53	59.06	38.47	20.39	73.82	48.34	25.48
Biggs Calif.	93	121-45	39-25	94	1914	1932		19	6	"		39.04		1.36	53.09	39.04	14.05	66.36	48.80	17.56
Big Springs Tex	94	101-23	32-15	2396	1916	1932		17	6	"		55.16		1.47	81.09	55.16	25.93	101.36	68.95	32.41
Burns, Oreg.	95	119-50	43-40	4125	1914	1919		6	6	"		46.22		1.30	52.29	40.22	12.07	65.36	50.27	15.09
Chillicothe, Tex.	96	99-00	34-20	1406	1912	1932		21	6	"	66.63	45.60 [2]	21.03	1.46	66.63	45.60	21.03	83.29	57.00	26.29
Colby, Kans.	97	101-20	39-30	3135	1914	1932		19	6	"		41.65		1.36	56.64	41.65	14.99	70.80	52.06	18.74
College Station, Tex	115	96-16	31-39	308	1916	1932		17	6	"	56.98	38.21 [2]	18.77	1.49	56.98	38.21	18.77	71.22	47.76	23.46
Coolidge La.	98	92-19	30-15	21	1910	1931		22	6	"		42.15		1.50	48.23	32.15	16.08	60.29	40.19	20.10
Dalhart, Tex	99	102-31	36-20	4000	1908	1916		9	8	"		35.06		1.40	77.08	55.06	22.02	96.35	68.83	27.52
" "					1917	1932		16	6	"		48.22		1.40	67.51	48.22	19.29	84.39	60.27	24.11
Denton, Tex	116	97-10	33-10	600	1917	1932		16	6	"	58.03	39.55 [2]	18.48	1.47	58.03	39.55	18.48	72.54	49.44	23.10
Dickinson, N.D.	27	102-48	47-00	2543	1908	1916		9	8	"		31.47		1.24	39.02	31.47	7.55	48.77	39.34	9.43
" "					1917	1932		16	6	"		34.70		1.24	43.03	34.70	8.33	53.79	43.38	10.41
Edgeley N.D.	100	98-44	46-22	1468	1908	1916		9	8	"		28.94		1.26	36.46	28.94	7.52	45.58	36.18	9.40
" "					1917	1920		4	6	"		29.80		1.26	37.55	29.80	7.75	46.94	37.25	9.69
Garden City, Kans.	101	100-52	37-48	2836	1908	1916		9	8	"		52.63		1.39	73.16	52.63	20.53	91.45	65.79	25.66
" "					1917	1932		16	6	"		54.79		1.39	76.16	54.79	21.37	95.20	68.49	26.71
Havre, Mont.	102	109-50	48-40	2505	1916	1932		17	6	"		35.36		1.22	43.14	35.36	7.78	53.93	44.20	9.73
Hays, Kans.	38	99-20	38-00	2000	1908	1916		9	8	"		47.93		1.36	65.18	47.93	17.25	81.47	59.91	21.56
" "					1917	1932		16	6	"		46.03		1.36	62.66	46.03	16.57	78.25	57.54	20.71
Hettinger, N.D.	103	102-40	46-00	2253	1911	1921		11	6	"		33.27		1.26	41.92	33.27	8.65	52.40	41.59	10.81
Iowa Park, Tex.	120	98-39	33-55	978	1926	1932		7	6	"	62.47	43.52 [2]	18.95	1.44	62.47	43.52	18.95	78.09	54.40	23.69
Lawton, Okla.	46	98-25	34-35	1111	1916	1932		17	6	"		43.78		1.43	62.61	43.78	18.83	78.26	54.73	23.54
Lubbock, Tex.	119	101-45	33-37	3106	1917	1932		16	6	"	62.16	42.06 [2]	20.10	1.48	62.16	42.06	20.10	77.70	52.58	25.12
Mandan, N.D.	52	100-54	47-00	1750	1914	1932		19	6	"		32.62		1.24	41.69	32.62	8.07	52.11	42.43	10.08
Moccasin, Mont.	104	109-30	47-15	4228	1910	1932		23	6	"		33.94		1.24	42.09	33.94	8.15	52.61	42.43	10.18

and water in the pan is maintained at approximately ground-level. Evaporation for April to September and that for May to October does not differ greatly and whichever of these quantities is available has been used to represent the evaporation for the six-month warm or growing season.

Relation of summer, winter, and yearly evaporation.--There are few records of evaporation for the six-month winter period north of latitude 37° north in the United States. For all stations listed on Tables 1 and 2 for which yearly evaporation records are maintained, the ratio (E_y/E_s)

of yearly evaporation to that for the six-month warm season was determined as shown in column (13) of Table 1 and column (15) of Table 2. This is the ratio by which the measured warm-season evaporation is to be multiplied to obtain the yearly evaporation.

For many purposes it is convenient to know the ratio of summer and winter season evaporation to the yearly total. For the summer season this is (E_s/E_y) or the reciprocal of the ratio given in Tables 1 and 2. For the winter season this quantity is $[1 - (E_s/E_y)]$.

Table 2--Summary of evaporation-records, Class-B stations--Concluded

Station	No.	Lat.	Elev.	Years Record	To	Years Used	Source of Pan	Pan Factor Fp	Observed Ys	Observed Ms	Ms/Ys	Ey	Ys/Ey	Observed Estimated Ys	Observed Estimated Ms	Observed Estimated W	Class A Data Ys	Class A Data S	Class A Data W
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)
Moro, Oreg.	107	45°30'	1800	1911	1931	21	G	0.69											
Hagerman, Tex.	111	34°-40	371	1915	1932	18	G	"	44.51	29.99 [a]	14.52	1.48	1.27	35.10	23.65	11.73	69.97	54.31	14.66
North Platte, Neb.	116	41°-20	2841	1908	1914	7	B	"	45.60		1.33	1.33	1.33	34.29	23.10	11.19	57.49	37.49	18.15
San Antonio, Tex.	121	29°-31	599	1907	1930	24	G	"	39.76	24.76 [a]	15.00	1.47	1.33	29.86	20.00	9.86	76.00	57.00	19.00
Sheridan, Wyo.	107	44°-50	3770	1911	1932	16	G	"	45.35	29.99 [a]	15.36	1.47	1.33	39.76	26.36	13.40	64.26	43.70	16.56
Spur, Tex.	122	33°-30	2274	1916	1932	17	G	"	44.46 [a]	21.89	22.57	1.47	1.47	65.35	44.46	21.89	82.13	55.82	26.31
Temple, Tex.	118	31°-15	740	1915	1932	18	G	"	44.39	24.39	20.00	1.47	1.47	65.35	44.25	21.10	55.51	42.80	12.45
Troup, Tex.	114	32°-20	484	1915	1932	18	G	"	45.45	29.99 [a]	15.46	1.52	1.52	69.33	45.51	23.82	82.91	54.39	28.52
Tucumcari, N.M.	100	35°-10	4194	1913	1932	20	G	"	45.45	29.99 [a]	15.46	1.48	1.48	67.14	44.41	22.73	73.73	49.09	24.64
Wheeler, Tex.	124	35°-29	80	1912	—	1	G	"	45.45	29.99 [a]	15.46	1.45	1.45	65.86	43.51	22.35	69.54	45.39	24.17
Willston, N.D.	109	48°-00	1875	1914	1917	4	B	"	45.45	34.11 [a]	11.34	1.62	1.62	73.70	54.27	19.43	74.56	47.76	28.54
Winter Haven, Tex.	125	27°-50	150	1931	1932	2	G	"	45.45	34.11 [a]	11.34	1.62	1.62	73.70	54.27	19.43	72.73	52.83	19.90
Woodward, Okla.	110	36°-30	1900	1914	1932	19	G	"	46.46	36.33 [a]	10.13	1.66	1.66	76.96	56.33	20.63	73.73	45.41	27.92
												1.48	1.48	68.24	45.11	23.13	50.43	41.33	9.10
												1.62	1.62	74.75	54.27	20.48	73.12	49.44	23.68
												1.40	1.40	64.50	44.25	20.25	70.53	50.38	20.15
												1.40	1.40	64.50	45.08	19.42	88.46	68.97	25.19

[a] May to October (inclusive).

Evaporation occurs mostly in the daytime and the ratio (E_s/E_y) is a function of the day's length and consequently of the latitude, increasing with the latitude, as shown by the line A of Figure 1, platted from group means of the ratios derived from the observations.

For comparison a similar line B was platted from the ratios of summer to yearly evaporation calculated by the HORTON evaporation-formula, for 112 United States Weather Bureau stations [2]. The calculated evaporation includes regions farther north and south than the observed data. The two lines are sensibly parallel and differ but slightly.

The line A on Figure 1 is represented by the equation

$$(E_s/E_y) = 0.42 + 0.008\,\phi \qquad (1)$$

where ϕ is the latitude of the station. This equation is empirical and was derived from data for latitudes between 29° and 37° north in the United States. It applies also to other latitudes and to the Southern Hemisphere, as shown by the values of the observed and computed ratios (E_s/E_y) given in Table 3.

Equation (1) supplies a much-needed means of determining approximately the evaporation during the cold season in latitudes where direct measurement of evaporation in winter is impracticable. This equation is based on observations at stations where but little freezing occurs. If equation (1) is applied to the determination of winter evaporation in a region where there is prolonged freezing, it may give results somewhat in error, and either too large or too small, dependent on conditions.

The temperature of an ice-surface is either 32°F if the air-temperature is higher or else has a value between the air-temperature and 32°F if the air-temperature is lower than 32°F, the ice-surface temperature approaching the air-temperature more and more closely as the ice-thickness increases. Evaporation-rate is governed largely by the temperature of the evaporating surface. For an ice-surface the evaporation-rate is generally below that for an open water-surface when the air-temperature is below 32°F and generally equals that for an open water-surface when the air-temperature is above 32°F.

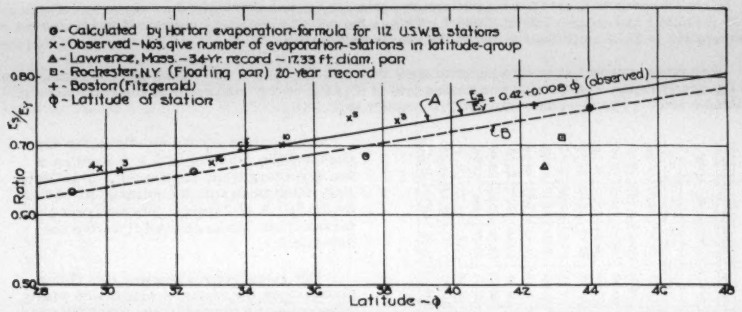

Fig. 1--Ratio of evaporation for May to October (inclusive) to yearly evaporation

Table 3--Ratio of evaporation for the six months' warm season to that for the year

Location (1)	No. of stations (2)	Latitude (3)	Ratio (E_S/E_Y) Observed (4)	Ratio (E_S/E_Y) Calculated (5)
England	12	52°.7 N	0.83	0.84
South Africa	6	29.0 S	0.667	0.652
Mexico	8	24.0 N	0.618	0.612

Data were found giving winter evaporation for three stations in northern United States. These are given on Figure 1.

At Mt. Hope Reservoir, Rochester, New York, evaporation is measured in winter by weighing an indurated-fibre tub, 16 inches in diameter, standing on a raft in the reservoir. The record for winter is not, however, comparable with the record for summer, when the tub is floated in an opening in the raft and the exposure to wind greatly reduced. As would be expected the ratio of summer to yearly evaporation given by this record is abnormally low.

DESMOND FITZGERALD [3] measured the evaporation from time to time under winter conditions at Boston, Massachusetts, and his results are in excellent agreement with those shown by line A.

A record of evaporation from a buried tank 17.33 feet in diameter was maintained throughout three years at Lawrence, Massachusetts [4]. During winter the ice was kept cut away from the rim of the tank and the chips piled back on the central ice-mass. These records show a ratio of summer to winter evaporation lower than that for a corresponding latitude as given by line A.

Using equation (1), values of (E_S/E_Y) were determined for stations for which warm-season evaporation only is measured. The reciprocals of these ratios are given in column (13) of Table 1 and column (15) of Table 2 and these factors were used to determine yearly and winter evaporation in these cases. In this way complete data for summer, winter, and yearly evaporation were obtained for all stations, as given in columns (14) to (16) of Table 1 and columns (16) to (18) of Table 2.

Correction to long-term mean--The Class-A pan-records used end with the year 1941 and extend back for various periods of years up to 25 years. The Class-B pan-records used usually end with 1932 and extend back usually ten years or more and in some cases 20 to 24 years. Evaporation is relatively more constant than rainfall or runoff and a study of the longer records showed that a record of 15 years' duration will give the long-term average evaporation usually within two per cent. In order to reduce all the records to the basis of long-term averages the evaporation

for a given station, covering a given period of years, was multiplied by the ratio of the long-term average to the evaporation for the same period of years at a nearby base-station having a 20- to 25-year record.

Sixteen base-stations were used, distributed over the United States. It was found that the ratio of evaporation for a given year or period of years to the long-term mean at a given station was sensibly the same for the year and for the summer alone, and because only summer records were available at many stations, the reduction to long-term mean was based entirely on ratios derived from summer records.

The final results, corrected to the basis of long-term means, are shown in columns (18), (19), and (20) of Table 1, and columns (16), (17), and (18) of Table 2. The base-stations used for reduction to long-term means are designated b in Table 1.

Relative evaporation from Class-A and Class-B pans--There are differences of size, form, and exposure of Class-A and Class-B evaporation-pans. Because of its more general use the Class-A pan is preferable as a standard of comparison.

Records of evaporation were kept with both a Class-A and a Class-B pan by BLANEY and YOUNG [5] at Baldwin Park Station, California, during the period July, 1932, to December, 1934, with one month missing. These observations show the following ratios of evaporation from the Class-A pan to that from the Class-B pan: Year, 1.20; November to April, 1.25. Winter in California corresponds nearly to summer conditions in the middle West, where Class-B pans are used. Evaporation as determined at Class-B stations, as given in Table 2, columns (16) to (18), have been multiplied by 1.25 to obtain the corresponding quantities for Class-A pans.

Evaporation-maps--For some purposes actual records of evaporation at individual stations are desirable and these are given in Tables 1 and 2. For general studies, evaporation-maps are to be preferred.

In 1888 THOMAS RUSSELL [6] published an evaporation-map of the United States, based mainly on observations with Piche evaporimeters. This type of instrument has been found to be generally unreliable and, even when operated in such a manner as to give a correct record, the amount of evaporation is greatly in excess of that from an evaporation-pan or other water-surface.

In 1911 BURTON E. LIVINGSTON [7] published a map showing the average weekly evaporation, in cc, throughout the United States, as derived from observations with cylindrical, white, porous-cup atmometers, during the period May 25 to September 7, 1908.

Recently A. F. MEYER [8] has published a map of monthly, seasonal, and annual evaporation from water-surfaces in the United States, using evaporation calculated by an evaporation-formula of the familiar Dalton type, with a special coefficient intended to give results applicable to lakes and reservoirs. The evaporation was calculated from temperature, humidity, and wind-velocity data derived at United States Weather Bureau stations. One of the greatest practical difficulties in calculating evaporation from such data is involved in reduction of wind-velocity from the various heights at which it is observed, to ground-level. Details of the method of reduction of wind-velocities to ground-level used by Meyer are not available.

The data shown in Tables 1 and 2 were platted for the warm and cold seasons and for the year, respectively, and evaporation-contours drawn, as shown on Figures 2, 3, and 4. These are apparently the first evaporation-maps of the United States based wholly on observations with pan-atmometers. The map for the warm season is of course the most reliable as it is based entirely on direct observations. The maps for the winter season and for the year are based in part on values of winter and yearly evaporation derived from the observed summer evaporation by the use of equation (1).

Use of evaporation-maps--Evaporation-data are used by ecologists, agronomists, meteorologists, hydrologists, and engineers. When used to determine evaporation from broad water-surfaces, such as those of lakes and reservoirs, an area-factor must be applied to allow for reduction of evaporation below that from a small pan by horizontal vapor-transport within the boundary-layer of laminar flow close to the liquid surface. G. I. TAYLOR [9] has given the following expression for the thickness t_g, in feet, of the boundary-layer of laminar or non-turbulent flow close to the ground

$$t_g = (0.0293/w) \qquad (2)$$

where w = wind-velocity in miles per hour. The thickness of the boundary-layer in moderate winds is slight--a few mm at most. Consequently the existence of the vapor-blanket over the water-surface is not readily detected by ordinary psychrometric measurements. The ratio of the evaporation from a broad water-surface to that from a Class-A evaporation-pan exposed on shore has commonly been found to be 0.60 to 0.80, and this numerical quantity is called the area-factor.

FOLLANSBEE [10] has compiled the following values of area-factor for Class-A evaporation-pans in some of the few cases where reliable determinations of this factor have been made.

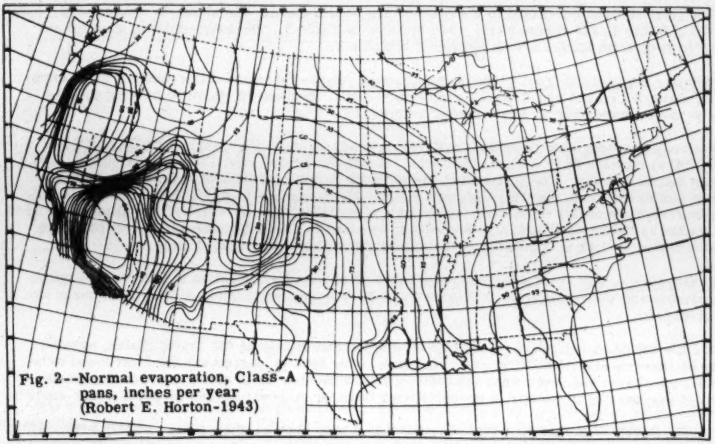

Fig. 2--Normal evaporation, Class-A pans, inches per year (Robert E. Horton-1943)

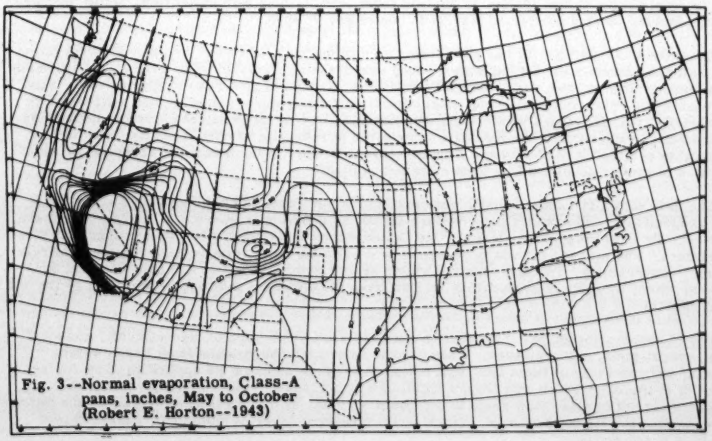

Fig. 3--Normal evaporation, Class-A pans, inches, May to October (Robert E. Horton--1943)

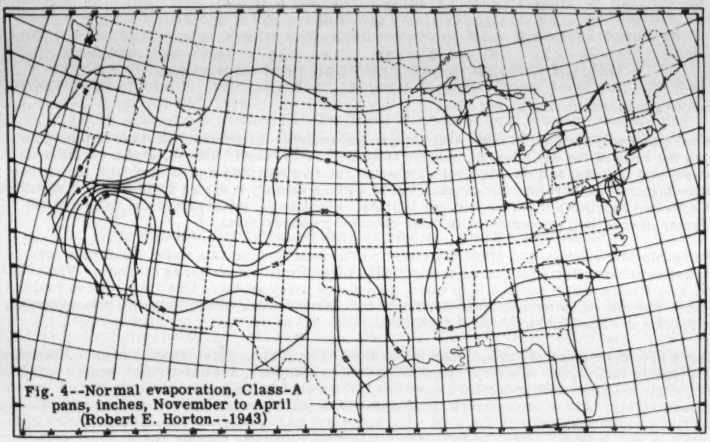

Fig. 4--Normal evaporation, Class-A pans, inches, November to April (Robert E. Horton--1943)

Table 4--Ratio of evaporation from Class A pans to that from larger water-surfaces

Location (1)	Years of record (2)	Comparison with (3)	Area-factor (4)
Denver, Colorado	1915-17	12-foot ground pan	0.70
Fort Collins, Colorado	1926-28	85-foot reservoir	0.70
East Park Reservoir, California	1930	1,800-acre reservoir	0.68
Milford, Utah	1925-27	12-foot ground pan	0.70
Lincoln, Nebraska	1917-20	7.5-foot ground pan	0.67
Salton Sea, California	1909-10	Indirect method	0.68
Salton Sea, California	1909-10	Indirect method	0.66

HORTON [2] has deduced a rational expression for area-factor based on the assumption that near the windward edge of a broad water-surface an unknown fraction m of the emitted vapor is carried to leeward, increasing the vapor-pressure and reducing the evaporation, until, at some distance x_c from the windward shore, the evaporation-rate becomes constant. The distance x_c is usually a few yards, and to the leeward of this point the evaporation bears the ratio to that from a land-exposed pan given by the equation

$$F = (1 - p) + p\,(\Psi - 1)/(\Psi - h) \qquad (3)$$

In this equation p is the fraction of the time during which turbulent flow prevails up to some considerable height above ground. Ψ is a wind-factor in the Horton evaporation-equation and is given by the equation

$$\Psi = 2.0 - e^{-k_a w}$$

where w is the wind-velocity at a height one foot above the water-surface and k_a is a constant having a value usually between 0.2 and 0.3, dependent on the evaporation-pan exposure. For $k_a = 0.3$ the values of Ψ are as follows:

w	= 0.0	1	2	3	4	5	6	
Ψ	= 1.0	1.18	1.33	1.45	1.55	1.63	1.70	
w	7	8	10	12	14	16	18	∞
Ψ	= 1.76	1.80	1.86	1.91	1.94	1.96	1.97	2.00

The relative humidity is designated h.

Wind commonly dies out at night near the ground-surface. In general the value of p may be taken as the ratio of the day's length, sunrise to sunset, to 24 hours. The value of p varies with the season and latitude, and the wind-velocity w and relative humidity h also vary with the season. The area-factor F is therefore not constant but at a given locality it varies from month to month and in different localities it varies with the latitude. Equation (3) gives numerical values of the area-factor in excellent agreement with those obtained by observation.

For ecological studies it is often desirable to determine evaporation under conditions corresponding to those under which transpiration takes place from leaf-surfaces of plants. The evaporation-rate from a small surface is greater, sometimes much greater, than that from an evaporation-pan. Porous-cup atmometers as developed by Livingston are often applied to measurements of evaporation in relation to ecological problems.

There are three types of porous-cup atmometers: The Bellani plate, three inches in diameter, area 7.1 square inches; the spherical cup, 2.05 inches in diameter, area about 12.5 square inches; and the cylindrical cup, with spherical closed end, diameter 1.1 inches, length three inches, area 10.4 square inches. These atmometers are also made in black and white. The Bellani plate exposes a flat surface parallel with the wind. The spherical and cylindrical cups create eddies and the three types of porous-cup atmometers are not hydrodynamically similar nor of equal areas and do not give equal amounts of evaporation. Evaporation from porous-cup atmometers is commonly recorded in cc. LIVINGSTON [7] found that for a white cylindrical porous-cup evaporimeter, exposed indoors at Tucson, Arizona, one cc from the porous-cup corresponded to an evaporation of 0.1416-mm depth from a copper pan 25 cm in diameter and 12 cm deep, filled to within five mm of the rim at each reading. At Salton, California, in 1909, one cc from a white cylindrical porous cup was found to correspond to 0.137 mm from a two-foot diameter evaporation-pan used by BIGELOW.

J. D. WILSON [11] has given a comparison of evaporation from black and white spherical porous-cup atmometers and a Class-A evaporation-pan at Wooster, Ohio, for the months May to September, and for the ten-year period, 1928 to 1937. The averages are: Black spherical atmometer, 6,635 cc; white spherical atmometer, 4,699 cc; Class-A United States Weather Bureau pan, 24.85 inches. Reducing the depth of evaporation from the white atmometer to equivalent depth of evaporation from the atmometer-surface gives an average of 57.8 inches or nearly 2-1/2 times the depth of evaporation from the Class-A pan.

The wide differences of evaporation-rate in the same location and climate but with different sizes and kinds of evaporation surface and exposure makes it difficult to adopt any single standard method of measuring evaporation that will meet all requirements. The maps of Figures 2, 3, and 4 furnish the relative evaporation-rates at different locations with comparable conditions as to instrument and mode of exposure.

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Voorheesville, New York

HYDROLOGIC INTERRELATIONS BETWEEN LANDS AND OCEANS

Robert E. Horton

Factors controlling precipitation--Rainfall in a given locality is governed by two sets of factors: (1) Hydrodynamic factors, such as topography and orographic conditions, which, together with atmospheric circulation, general and local, determine the occurrence and frequency of ascending air-masses; (2) moisture-supply. Either of these factors may be adequate to produce rain but if the other is deficient, little or no rain occurs. Air-masses rich in moisture pass in summer from the Pacific Ocean over the coastal plains of California, producing little or no rain until forced above the condensation-level by the coastal mountain ranges.

Relatively dry air-currents ascending mountain slopes in the eastern Rocky Mountain Region produce little rain because of low moisture-content and consequent high condensation-level. Heavy rain generally occurs when the two sets of factors described are both present, as in case of the Blue Ridge Mountains, certain mountain regions in Hawaii, the Mt. Hood region in Washington, and the western Ghats in India. In the upper Mississippi Valley nearly 80 per cent of the total annual rainfall occurs in the six-month warm season, May to October, in spite of the remoteness from the ocean and absence of mountains. This results chiefly from conditions favoring convective and frontal ascent of air and the presence of moisture derived from inland water-losses to windward.

General hydrologic data for the United States--As a basis for the discussion of the interrelations of lands and oceans, certain hydrologic data for continental United States, excluding Alaska, have been compiled as shown in Table 1. A report of the National Resources Board [see 1 of "References" at end of paper] contains maps of average annual precipitation and average annual runoff throughout the United States. The average annual rainfall was determined from the contours for each 2° quadrangle of latitude and longitude; the average annual runoff was similarly determined; the difference between the two represents the average annual water-losses in the 2° quadrangle. Averaging these values for the whole of the United States for either rainfall, runoff or water-losses,

TABLE 1 - RAINFALL, RUNOFF, WATER-LOSS AND EVAPORATION - CHARACTERISTICS REGIONS OF UNITED STATES

Region	Area		Precipitation		Runoff		Water-loss		Evaporation	
	Sq. Mi.	% Total	P Average Inches	% Total	Y Average Inches	% Total	L Average Inches	% Total	E Average Inches	% Total
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Continental United States	3,026,789	100.0	31.5	100.0	10.6	100.0	20.9	100.0	58.2	100.0
Area East of Continental Divide	2,104,127	71.5	32.8	74.4	9.6	64.9	23.2	79.7	54.6	67.2
Area West of Continental Divide	862,662	28.5	28.3	25.6	13.2	35.1	15.1	20.3	66.9	32.8
Great Basin	230,758	7.6	14.0	3.4	3.5	2.5	10.5	3.8	90.0	11.8
Peripheral Area - West of Continental Divide	631,904	20.9	30.3	20.1	14.4	26.5	15.9	16.0	63.7	22.9
Peripheral Area - Total United States	2,796,031	92.4	32.8	96.6	11.0	97.5	21.8	96.2	55.4	88.2
4° Belt - West coast	224,326	7.4	49.4	11.6	28.5	20.8	20.9	7.4	69.3	8.9
4° Belt - East coast	323,275	10.7	45.1	15.3	18.9	19.1	26.2	13.4	43.4	8.0

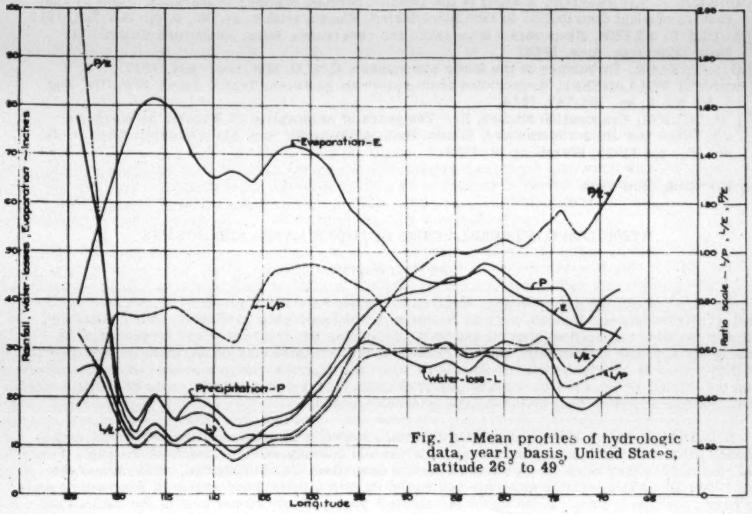

Fig. 1--Mean profiles of hydrologic data, yearly basis, United States, latitude 26° to 49°

or for any given portion, the average quantities were obtained for different physiographic regions, as shown in Table 1.

Data for average evaporation from Class-A, United States Weather Bureau evaporation-pans were similarly obtained from evaporation-maps prepared by the author [2]. The average rainfall is 31.5 inches, the average runoff 10.6 inches, the average water-losses 20.9 inches or about two-thirds of the rainfall. The average evaporation from Class-A pans is 58.2 inches, the average evaporation from broad water-surfaces is about 70 per cent of this or roundly 41 inches, or approximately twice the average water-losses.

From the data described, values of the ratios water-loss to precipitation = (L/P), water-loss to evaporation = (L/E), and precipitation to evaporation = (P/E) were determined for each 2° quadrangle. Figure 1 shows an average profile of the various hydrologic elements described, proceeding eastward from the Pacific Ocean to the Atlantic Ocean. Data for this profile were obtained by plotting the values of a given element for each 2° of latitude and for a given longitude.

There will be occasion later to use the data given in Table 1 and on Figure 1 in various ways, but first some general considerations of the hydrologic interrelations of lands and oceans will be developed.

Vapor-exchange--Much attention has been given to the relation of water-losses to precipitation. This paper is largely devoted to the converse question or the relation of precipitation to water-losses. This involves the interchange of vapor between a given area and the surrounding terrain and in particular the interchange of vapor between land-areas and the oceans.

In dealing with the question of the extent to which precipitation in a given locality is derived, respectively, from "oceanic vapor" and "vapor of local origin" it is necessary, in order to avoid confusion, to specifically define the kinds and sources of vapor under consideration. These may include:

(1) Vapor truly of oceanic origin, derived by direct evaporation from ocean-surfaces.
(2) Vapor imported from the ocean to the land and vice versa. In some localities, especially adjacent to coast-lines, this may include not only vapor derived through evaporation from ocean-

surfaces but also vapor previously exported from the land to the ocean and later returned to the land without precipitation.

(3) Net vapor-exchange--This is the net exchange of vapor between the ocean and the land, regardless of the source of vapor. With respect either to the land or ocean it is the difference between the vapor exported and the vapor imported. This quantity is sometimes referred to as if it were all vapor of truly oceanic origin or as if it represented all the vapor of true oceanic origin entering the land. Neither of these assumptions is necessary nor generally true. Net exchange of vapor is by far the most important of the three quantities described, since it alone determines the water-balance between the oceans and continents.

Wide differences in numerical results may follow attempts to estimate the amount of inland precipitation derived from "oceanic vapor," dependent on which of the three quantities defined is considered to represent "oceanic vapor."

In dealing with the amount of precipitation on a given land-area or drainage-basin derived, respectively, from oceanic and non-oceanic vapor, distinction must be made between vapor derived from water-losses on the given area and vapor also of inland origin imported from adjacent land-areas. The former may conveniently be called "indigenous" or "native" vapor and the latter "exotic vapor of land-origin." In case of an inland area there is, disregarding true oceanic vapor, usually a net vapor-exchange between the given area and the surrounding terrain. With respect to a given land-area the precipitation may be derived in part from each of the three following types of vapor: (1) Native vapor; (2) exotic land-vapor; (3) vapor of true oceanic origin.

Hydrologic balance of a drainage-basin--If the inflow of water in any form to a drainage-basin is balanced with the outflow, then for surface- and subsurface-conditions the equation of continuity gives the result

$$P = y + L + \Delta_s \tag{1}$$

where P = precipitation, y = total runoff, L = evaporative water-losses, and Δ_s = gain or loss of storage in the time-interval under consideration, all quantities being expressed in the same units. This equation holds true for any time-interval and applies to any drainage-basin and to the Earth as a whole.

For steady conditions Δ_s must be zero, since otherwise either dessication or the reverse would occur. For $\Delta_s = 0$

$$P = y + L \tag{2}$$

or

$$y = P - L \tag{3}$$

Next consider the drainage-basin as surrounded by a permeable shell extending up to the limit of vapor-circulation. Let O, C, and L represent, respectively, the quantities of vapor entering or leaving this shell and which are derived directly from evaporation from oceans, from lands extraneous to the area and from the area itself, and let R represent the resultant net vapor-exchange between the atmospheric shell and its surroundings. The subscripts i and e will be used to designate vapor flowing into and out of the shell, that is, imported and exported vapor, respectively. For vapor of a given origin, that which merely passes over and through the atmospheric shell need not be separately considered. The prefix Δ will be used to designate the net difference between import and export of vapor of a given kind. Then for atmospheric conditions over a given area the storage-equation for steady conditions gives

$$P = (L - L_e) + \Delta O + \Delta C \tag{4}$$

and

$$R = P - L = \Delta O + \Delta C - L_e \tag{5}$$

Equating (3) and (5) gives

$$y = \Delta O + \Delta C - L_e = R \tag{6}$$

or the resultant vapor-transfer or net vapor-exchange between the given area and its surroundings

is precisely equal to the runoff. This rule is true for any area, large or small, on which precipitation occurs. It applies equally well to the drip from a single leaf of a broad-leaved tree, to a drainage-basin draining directly to the ocean, to a remote interior tributary of a stream draining to the ocean, to a closed interior basin, to the continents as a whole or to the oceans alone.

The statement is sometimes made that the runoff from the land-surfaces of the Earth to the oceans is equal to the vapor imported from the oceans to the land. This statement is precisely true if the term "vapor imported from the oceans" means "net vapor-exchange" between the oceans and the lands.

With respect to an individual area the statement may also be made that the runoff passing out from the area is precisely equal to the net vapor-exchange between the given area and its surroundings. This does not mean that the quantity of vapor actually of oceanic origin transferred from the oceans to the land equals the runoff from the land. There are, in fact, large differences in the quantity of vapor actually of oceanic origin transferred to the land under different conditions, even though in every case the net vapor-exchange between the ocean and the land-area of the given drainage-basin is, for steady conditions, precisely equal to the runoff.

Inland drainage-basins--The term "inland drainage-basin" will be used to describe a basin more or less remote from the ocean but which produces runoff to the ocean through a larger stream to which the given drainage-basin is tributary. An inland drainage-basin is not to be confused with an interior or closed drainage-basin which produces no runoff to the ocean. In most cases the determination of the quantities of vapor of any actual source of origin contributing to precipitation on an inland drainage-basin is complicated by the fact that the vapor-exchange may take place through a series of barters, much as a Chinese fur-importer may buy furs gathered by a Canadian voyageur through various intermediaries, and although the voyageur is not paid in Chinese money, the exchange is nonetheless real and there is an export of money from China equal to the value of the furs, and an export of fur from Canada equal to the value of the money.

Consider next the case of a single leaf of a broad-leaved tree. Rain dripping from the leaf represents runoff, and this may pass through various stream-channels, finally reaching the ocean. In this case it is improbable that any of the vapor emitted from the leaf by transpiration and evaporation of intercepted rain is reprecipitated on the leaf--in other words, all the vapor originating on the leaf-area is exported and $L_e = L$. For these conditions equation (6) gives

$$y = \Delta 0 + \Delta C - L = R \qquad (7)$$

Again the resultant vapor-exchange between the leaf and its surroundings equals the runoff from the leaf. Equation (7), however, gives no clue as to the fractions of this vapor-exchange represented, respectively, by oceanic vapor $\Delta 0$ and vapor from adjacent land-areas ΔC. This relation depends largely on the position of the tree, whether closely adjacent to or remote from the ocean. Since, however, the runoff into the ocean from the leaf can be considered by itself, it is still true that there is a net vapor-exchange between the ocean and land adjacent to the ocean precisely equal to the runoff from the leaf. If this exchange was, for example, vapor wholly of oceanic origin, still there might be other exchanges between the coast-line and the location of the tree such that none of the vapor finally precipitated on the leaf would be derived directly from evaporation from the ocean. Confusion has arisen in dealing with this problem through failure to take into account the difference between the resultant vapor-transfer, regardless of the origin of the vapor, and the quantity of vapor of a given kind which is transferred in a given case.

Milk River rises in Alberta Province, Canada, and discharges its runoff through Missouri and Mississippi rivers into the Gulf of Mexico, more than 2,000 miles away. There is a net vapor-exchange between this drainage-basin and the Gulf of Mexico or Atlantic Ocean equal to the runoff, but the vapor which finally arrives on Milk River Drainage-Basin may none of it come from the Gulf of Mexico. Athabasca River, rising near the same point in South Alberta, discharges into the Arctic Ocean through Mackenzie River. There is a net vapor-exchange between this drainage-basin and the Arctic Ocean equal to the runoff, but again little or none of the actual vapor may have originated in the Arctic Ocean 1,200 miles to the north. In these two cases the vapor actually replacing the runoff is undoubtedly derived both directly and indirectly from the same sources, chiefly from evaporation from the Pacific Ocean and from land surrounding the two drainage-basins. Abstraction of water from the Pacific Ocean is replaced by an exchange through ocean-currents.

In case of an inland drainage-basin with precipitation P and runoff y, there is a net vapor-exchange with the ocean equal to a fraction (y/P) of the precipitation, although the drainage-basin may receive little or no vapor actually of oceanic origin. Conversely, the precipitation on a coastal

drainage-area or an oceanic island may nearly all be derived from vapor evaporated directly from ocean-surfaces although the area or island is dependent on oceanic vapor for only a fraction (y/P) of the precipitation.

Interior drainage-basins--Interior or closed basins constitute about 20 per cent of the land-surfaces of the Earth, some of the larger being those of Salt Lake, the Dead Sea (1,290 feet below sea-level), the Caspian Sea (84 feet below sea-level), Lakes Baikal, Balkash, and the Aral Sea in Asia. Most closed basins produce runoff from their higher land-areas but this is lost by evaporation from playas or undrained lakes and none of it reaches the ocean.

For a closed basin which is neither undergoing dessication nor the reverse, the net vapor-exchange R is zero but, from equation (6)

$$R = \Delta 0 + \Delta C - L_e = 0 \qquad (8)$$

and such an area may actually receive vapor from contiguous lands or from the ocean and export some of the native vapor. If the quantities of vapor imported and exported do not balance, then the basin either undergoes dessication or is increasing in humidity. Dessication has occurred over long periods of years in Salt Lake Drainage-Basin, Utah, and Winnemucca Lake Drainage-Basin, Nevada, indicating that during these periods native vapor has been exported in excess of imported vapor from extraneous sources.

Seasonal cycle of storage and vapor-exchange--Rainfall and evaporation are readily determined separately for the warm or summer, and for the cold or winter, seasons. In most regions water is carried forward from the cold to the warm season in the form of stored soil-moisture, ground-water, storage in lakes, swamps and marshes, and in mountain regions as snow- and ice-fields. This water is disposed of in the warm season as runoff or water-losses. The difference (P - y) between rainfall and runoff for either the warm or cold season, considered alone, does not therefore represent the actual water-losses but instead it may be designated the apparent water-losses, L'. In order to determine the actual water-losses it is necessary to correct the apparent water-losses for gain or loss of storage in the drainage-basin. Requisite data for making this correction are not always available. The correction varies from zero for impervious areas without lakes or ground-water, up to several inches depth on the drainage-basin for areas with deep soil, abundant ground-water, or with large lakes or snow-fields. From field-studies, COLE, MATTHEWS, and CHILCOTT [5] found, in the western Mississippi Valley, from one to three inches of water were abstracted from previously stored soil-moisture during the crop-season on lands planted to spring wheat. This was equivalent to 20 to 40 per cent of the total water used by the crop. Similar use of soil-moisture storage in the growing season occurs also in the corn-belt. Studies of the abstraction of water from ground-water storage as ground-water runoff during the warm season shows that this varies from zero in semi-arid and arid regions where there is no perennial water-table, up to two to four inches in eastern humid regions with moderately deep permeable soil and abundant rainfall and ground-water. While precise figures are unavailable, it is certain that the average depletion of storage in the warm season throughout the United States is of the order of at least two inches on the land-surface. There is a corresponding accretion of storage during the cold season. Storage of moisture as vapor in the atmosphere can rarely exceed two inches depth of water. The air, even that which has recently produced rain, contains moisture, so that the available storage of moisture in the atmosphere, on an average, is only a fraction of an inch in depth. The seasonal cycle of gain and loss of storage from land-areas is therefore necessarily accompanied by a corresponding seasonal loss and gain of storage in the oceans.

The water-losses from land-areas in the warm season average about 85 per cent of the precipitation. Under conditions like those existing in the upper Mississippi Valley, the actual water-losses may exceed the precipitation during the warm season, as part of the water-losses are derived from antecedent storage. Under these conditions there is transferred from the land to the ocean during the warm season not only the runoff but a certain amount of net vapor-exchange, which is precipitated on the ocean-surface, and these two items build up ocean-storage during the summer season.

During the cold season the water-losses from land-areas represent only about one-third of the precipitation. The remaining precipitation is made up by net vapor-exchange from the oceans and part of the precipitation goes into storage, which is carried forward to the warm season. While the runoff in the cold season is usually greater than in the warm season, it is not sufficient to balance the net vapor-exchange between ocean and land, with the result that in the cold season there is depletion of ocean-storage. The relation between the principal hydrologic factors for the warm and cold seasons in the United States as a whole and on the peripheral areas is shown approximately by the figures in Table 2.

Table 2--Hydrologic relations, warm and cold seasons

Relation	Warm	Cold	Year
	Per cent of annual		
P	57	43	.....
y	35	65	.....
L′	65	35	.....
L	75	25	.....
E	75	25	.....
	Depth in inches, whole United States		
P	18.0	13.5	31.5
y	3.7	6.8	10.5
L′	13.6	7.4	21.0
L	15.7	5.3	21.0
E	42.0	16.0	58.0
	Depth in inches, peripheral areas		
P	18.7	14.1	32.8
y	4.8	6.2	11.0
L′	14.2	7.6	21.8
L	16.2	5.6	21.8
E	41.0	14.0	55.0

The figures given in Table 2 are illustrative rather than precise, as they have been derived from various sources by various methods. As to rainfall, its division between warm and cold seasons is definitely known. Runoff during the warm season ranges from a few per cent of the annual total in semi-arid regions where only ephemeral runoff occurs and there is no water-table, up to about 40 per cent of the annual total in the upper Mississippi Valley, where approximately 80 per cent of the precipitation occurs during the warm season. In the upper Tennessee Valley and Blue Ridge Mountain regions, with rainfall from 60 to 80 inches per year, quite equally divided between warm and cold seasons, about 30 per cent of the runoff occurs during the warm season, while in case of western mountain streams having their sources above the snow-line, more than 50 per cent of the runoff occurs during the warm season. Table 2 indicates an increase of storage on the land-area in the cold season equivalent to two inches depth and a corresponding depletion of land-storage in the warm season. About three-fourths of the actual water-losses occur in the warm season and only about one-third the total runoff.

The seasonal cycle of transfer of storage between the land and the oceans does not necessarily affect the annual water-balance or the total amount of precipitation received on the land. If this exchange of storage in liquid form did not occur there would still be net vapor-exchange between the oceans and land but it would be more nearly continuous and a larger proportion of the annual precipitation would occur in summer and a smaller proportion in winter. Indirectly this would affect the water-losses, which occur mostly in summer and increase with increasing precipitation up to a limit determined by the evaporation-rate.

A similar cycle of exchange of storage between lands and oceans occurs in connection with each succession of dry and wet periods. If the net vapor-exchange between a drainage-basin and its surroundings took place at a continuous and uniform rate, then, because of the small atmospheric storage, all native vapor must soon be reprecipitated and the total rainfall would be equal to native vapor plus runoff. Actually vapor is exported during dry periods and imported during rainy periods and this results in the concentration of the precipitation on the land in a smaller number of heavier rains. This has important economic effects. Very light rains in general produce neither direct surface-runoff nor ground-water. Neither do they penetrate the soil sufficiently to support other than shallow-rooted vegetation. The economic value of both streams and lands depends to a large extent on the occurrence of "soaking" rains, and the exchange of storage between the lands and oceans, in conjunction with vapor-exchange, favors the occurrence of such rains.

Evaporation, water-losses, and vapor-transfer--The storage-equation gives a basis for determining the net vapor-exchange under all conditions but it does not provide a quantitative basis for determining the relative quantities of vapor of different origins precipitated on a given area. Other lines of evidence are available which throw light on the composition of precipitation in terms of fractions of vapor derived from different sources. These include:

(1) The sources, characteristics, and frequency of occurrence of air-masses passing over the given area
(2) Considerations of the relative occurrence of evaporation and water-losses in wet and dry periods
(3) Chemical composition of rain, particularly its chlorine-content
(4) The equations of rain-profiles

HOLZMAN [3] and HOLZMAN and THORNTHWAITE [4] have considered the relation of air-masses to precipitation and have pointed out that evaporation from water-surfaces mostly occurs during dry periods and that much of the vapor originating over inland water-bodies in fair weather is carried aloft and thence passes out over the ocean. With the exception of the Great Lakes,

water-surfaces of lakes, reservoirs, and streams in the United States occupy only a minute fraction of the land-area. The extent to which precipitation on a given land-area is derived from native and exotic land-vapor rather than from true ocean-vapor is determined chiefly by water-losses from land-areas and not by evaporation from open water-surfaces. Figure 1 shows that evaporation from water-surfaces decreases quite rapidly proceeding from the Great Basin eastward to the Atlantic coast. Water-losses, on the other hand, gradually increase proceeding from the Great Basin to the Atlantic Ocean.

The relation between water-losses in rainy and fair weather is also to a considerable degree the converse of the relation of evaporation from water-surfaces under the two conditions. Water-losses--all evaporative in nature--are of three kinds: (1) Direct interception by vegetation; (2) transpiration; (3) evaporation from the soil.

Interception occurs only during and immediately following rain and involves two items: (1) Direct evaporation from leaves and stems of plants during rain; (2) evaporation of interception-storage immediately following rain. Everyone who has stood under a tree to escape a passing shower knows that with good vegetal cover interception may dispose of 100 per cent of a light shower. Various series of experiments show that the percentage of rain disposed of by interception varies inversely as the rain-intensity and increases with the density of vegetal cover. In general, for areas with mixed vegetation, some forest and most of the remaining area cropped land, interception takes a toll of ten to 20 per cent of the precipitation in summer and about an equal fraction in winter, in spite of the absence of growing crops and leaves on deciduous trees. The approximate equality of the interception-percentage in summer and winter results chiefly from the lower rain-intensities prevailing in the cold season. Interception represents generally about 30 per cent of the total water-losses and this 30 per cent occurs only during or immediately following rain.

The question naturally arises how so large a percentage of rain can be disposed of by interception in view of the low rate of evaporation during rain. Evaporation nearly always continues during rain and the humidity is rarely 100 per cent during rain. The evaporation-rate from Class-A evaporation-pans is, however, but a small percentage of that in fair sunny weather. Three factors are involved:

(1) The evaporation-rate from small surfaces, such as individual leaves and twigs, is much higher, other things equal, than that from an evaporation-pan or a broad water-surface. WILSON [8] made a ten-year comparison between evaporation from a black porous-cup atmometer and a Class-A evaporation-pan during the summer season. The water-loss from the former, measured in inches depth on the exposed surface, was 3.5 times that from the evaporation-pan. This is believed to be fairly representative of the evaporation-rate from the leaves and stems of plants.

(2) The total leaf- and twig-surfaces with good vegetal cover is much greater--often five to ten times greater--than the projected or ground-area. The combination of these factors permits evaporation from plant-surfaces to take place during rain at a rate, measured in terms of depth of water on the ground-surface, of the same order of magnitude as in fair weather.

(3) The third factor is interception-storage, which amounts to as much as 0.05-inch depth with good vegetal cover, and with 100 showers during the six-month warm season this may dispose of as much as five inches of rain.

The most important element of water-loss is transpiration by vegetation. For cropped or forest areas transpiration disposes of an amount of water in the form of vapor of the same order of magnitude as the total runoff. Transpiration under ordinary fair-weather conditions is quite closely correlated with the same physical factors which govern evaporation but under extreme conditions, for example, either during rain or in severe drought, this is not true. MAXIMOV [9], from a careful review of the extensive literature of the subject, concluded that while there is a fairly close correlation between transpiration and humidity within a certain range of relative humidity, yet "with an increase of relative humidity the rate of transpiration increases; with a decrease of relative humidity the rate diminishes." F. DARWIN [10] concluded that transpiration does not stop at 100 per cent humidity but may continue with supersaturation up to 105 to 110 per cent.

It appears certain that as long as there is soil-moisture available contiguous to plant-roots in an amount ranging from that at the wilting-point to that at capillary capacity, the rate of intake of water is nearly independent of the soil-moisture. Moisture may be present in adequate quantities in adjacent soil after it has become exhausted to the wilting-point closely adjacent to plant-roots. Thereafter the roots can absorb moisture only as fast as it is transmitted by the slow process of capillary flow from more and more remote regions of the soil, and under these condi-

tions, which occur in dry periods, the transpiration-rate is materially diminished. Apparently the rate of transpiration-loss per unit of time, other things equal, is of the same order of magnitude in rainy and fair weather, except in extremely dry periods, when it is reduced. Evaporation from a soil-surface fully wetted takes place sensibly at the same rate as from a water-surface, other things equal. During fair weather, following rain, moisture close to the soil-surface becomes rapidly exhausted, so that the water-losses by direct evaporation from the soil will generally be much greater than during rain for a time after rain ends and thereafter will be less than during rain.

The preceding discussion relates chiefly to rates of water-loss per unit of time. The duration of rain is in general only a small percentage of the total time but the duration of conditions favoring rain, either on a given area or adjacent areas, is of the same order of magnitude as the duration of low-pressure areas on a given drainage-basin, or roughly one-fourth to one-third of the total time. All things considered, the rate of water-loss during conditions favoring rain is apparently not greatly different from and may sometimes exceed the average rate but the duration of conditions favoring rain is less than the duration of fair weather, so that the greater portion of the total water-losses occurs in fair weather under conditions such that vapor originating as water-losses is likely to be transported outside a given drainage-basin and either reprecipitated elsewhere or carried to the ocean.

The discussion thus far relates wholly to conditions during the warm or growing season. In the cold season, if there is snow-cover or, as is usually the case, the soil-surface is nearly saturated, direct evaporation from the soil occurs continuously at a rate governed by the evaporation-rate. Interception occurs much as in summer but there is no transpiration. The water-loss is in general considerably greater during and immediately following rain than in fair weather.

The chlorine-content of rain and runoff--Chlorine in runoff may occur as the result of carrying into solution from rock or soil of compounds containing chlorine or as the result of the precipitation of rain derived from ocean-vapor and containing salt-particles as condensation-nuclei. Where several types of nuclei are available, condensation takes place most rapidly on the larger particles and those having certain physical and chemical properties. Salt-particles are among the larger nuclei and are highly hygroscopic and, where available, they form the principal condensation-nuclei of cloud and rain-droplets. Along the coast salt-nuclei are derived from ocean-spray and from the breaking of waves on the shoreland are generally plentiful beyond condensation-requirements, and it may be assumed that nearly all vapor-particles derived from vapor passing inland from the oceans contain salt-nuclei.

The presence of excessive chlorine in potable waters is presumptive evidence of dangerous pollution. Extensive determinations of chlorine in runoff-waters have been made and, in addition to their use in interpretation of the quality of water, these data serve other purposes, as in the determination of the age of the Earth from the amount of sodium carried into the oceans by streams, and as a basis of determining sources of moisture in the study of air-masses and the interpretation of rainfall-maps.

In connection with the last-named problem the following notation is used, quantities of rainfall and runoff being expressed in inches depth and chlorine-content in parts by weight per million.

P = total precipitation
P_o = precipitation derived from ocean-vapor
P_ℓ = precipitation derived from vapor of land-origin
y = total runoff
y_o = runoff derived from ocean-vapor
y_ℓ = runoff derived from land-vapor
C_y = chlorine-content of the runoff
C_r = chlorine-content of rain of oceanic origin

Primes are added to the corresponding quantities to relate them to an inland location x where the fractions of rain derived from ocean-vapor and land-vapor, respectively, are to be determined. In connection with land-areas the term "ocean-vapor" is used in the sense of vapor passing inland from the ocean. It may or may not all have originated as evaporation from the ocean; some of it may have been carried to the ocean from the land in air-masses, mixed with ocean-vapor and later returned to the land.

Along the coast the solutional chlorine in runoff is usually small relative to the chlorine derived from rain and may for the present be neglected. Then for coastal conditions

$$C_r = (y/P)\, C_y \qquad (9)$$

At the interior location x it may be assumed that all the chlorine C_y in runoff is derived from that in the fraction P'_o of the rainfall at x. This assumption will only be true if the solutional chlorine is first deducted or is negligible in amount. That it will then be true is evident from the fact that part of the rain of oceanic origin and containing chlorine goes directly into the runoff, while the remainder is evaporated and the chlorine remains behind and sooner or later appears in the runoff. Under these conditions

$$C_r P'_o = C'_y y' \qquad (10)$$

and

$$(P'_o/P') = (C'_y/C_r)\,(y'/P') \qquad (11)$$

Substituting the value of C_r from (9) in (10) and (11) gives

$$(P'_o/P') = C'_y/C_y)\,(P/y)\,(y'/P') \qquad (12)$$

and

$$(P'_{\bar{g}}/P') = [1 - (C'_y/C_y)\,(P/y)\,(y'/P')] \qquad (13)$$

Equations (12) and (13) show, respectively, the fractions of precipitation at x derived from vapor originating over the ocean and land. This analysis takes into account the effect of differences of rainfall and water-losses at the coast and at the inland location, respectively, on the concentration of chlorine and runoff. If a map of chlorine-content of waters at the coast and at the location x, together with data of rainfall and runoff, are known for the two locations, then the fractions of rain derived from ocean- and land-vapor, respectively, can be determined.

On the Atlantic Coast, in the vicinity of New York City, P = 45 inches, y = 22.5 inches, and C_y = 6.0. In the lower Genesee River Valley, in western New York, about 300 miles from New York City, P' = 30 inches, y = 12 inches, and C'_y = 0.3. From equation (4), (P'_o/P') = 0.04, or about four per cent of the rain is derived from oceanic vapor and 96 per cent from vapor originating over land. Even this result is somewhat too large, as a part, apparently about 0.1 part per million (ppm) of the chlorine-content of runoff in the Genesee Valley, 0.3 ppm, is solutional chlorine. In this case if the ratio of runoff to rainfall had been the same in the two cases, then the fraction of rain derived from ocean-vapor would be five per cent.

Professor DANIEL D. JACKSON [6] published a map showing the isochlors or normal quantity of chlorine-content in unpolluted waters, in ppm, in New York and the New England States. In this region there are few local sources of chlorine in unpolluted runoff and the quantity of solutional chlorine is small--apparently not exceeding 0.2 ppm. Figure 2 shows a chlorine-profile derived from Jackson's map, along the Hudson and Champlain valleys, together with the rain-profile.

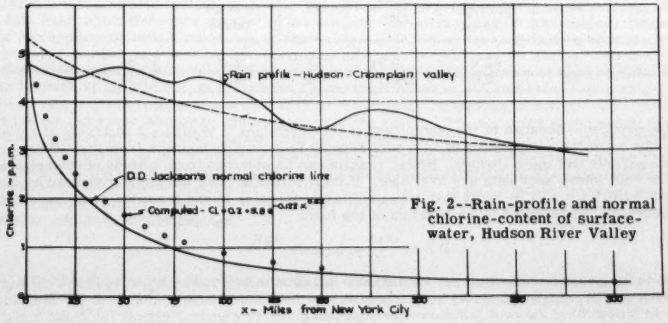

Fig. 2--Rain-profile and normal chlorine-content of surface-water, Hudson River Valley

Subject to the effect of local variations of rainfall and runoff, the chlorine-content of surface-runoff is quite closely represented by the equation given in Figure 2. It will be noted that at a distance exceeding 300 miles from the coast-line, only solutional chlorine is contained in the run-off. This indicates that in this region rain derived from oceanic vapor is limited to a coastal belt about 300 miles in width. Within this belt the fraction of rain derived from oceanic vapor decreases in accordance with an inverse exponential law, as would be expected from the fact that processes of exhaustion are involved, the amount of rain derived from oceanic vapor being proportional to the amount of oceanic vapor remaining in the air-currents producing rain. The width of the coastal belt in which rain is derived from oceanic vapor diminishes in case there is a mountain mass adjacent to the coast-line. Such mountain masses exist throughout nearly the whole length of the Atlantic and Pacific coast-lines of North America. The oceanic vapor is precipitated more rapidly as a result of orographic effects than would be the case if the land rose gradually and uniformly proceeding away from the coast-line, as happens in the lower Mississippi Valley.

Results similar to those obtained for New York and New England are certainly applicable to the Pacific coastal mountain regions as regards inland distribution of rain derived from oceanic vapor. Precise calculations cannot be made for the reason that there are local sources of solutional chlorine, particularly in case of storm-runoff from playas and alkaline soils on or into which large quantities of salts have been deposited by evaporation, thus making it impossible to determine the normal chlorine-content of unpolluted waters from the data presently available. In the case of the Mississippi Valley the slope is gradual proceeding inland. Low-pressure areas crossing central and northern United States from the Pacific toward the Atlantic carry with them oceanic vapor containing chlorine, some of which still remains in the dryer air descending onto the plains east of the Rocky Mountains. Air-currents from the Gulf of Mexico containing chlorine tend to flow into low-pressure areas crossing the United States, the amount decreasing with the distance inland. Some chlorine of oceanic origin reaches the upper Mississippi and Missouri River valleys from one or both of these cources.

Records of chlorine (as chlorides) in rain and snow at Mt. Vernon, Iowa, have been given as in Table 3 by HENDRICKS [7]. The weighted average amount of chlorine in 28.37 inches of precipitation in 42 storms analyzed during the seven-month period, November, 1926, to May, 1927, was 3.95 ppm. Seventy per cent of the chlorine was contained in two snowstorms in January, 1926. Omitting these the weighted average chlorine in 40 storms was 1.17 ppm and in one-half of these rains no chlorine occurred. Taking the normal coastal chlorine in coastal rain as six ppm it appears that in the central Mississippi Valley about one-fifth of the rain is normally precipitated from ocean-vapor, chiefly in winter, but exceptional storms may occur in which as much as two-thirds of the precipitation is from vapor of oceanic origin. In the region referred to this represents a large proportion of the winter precipitation. In one-half of the rains there was no chlorine, indicating that the vapor producing the rain was wholly of non-oceanic origin. If chlorine occurred it was likely to be found to the extent of several parts per million.

Table 3--Chlorides in precipitation, Mt. Vernon, Iowa

[Mon. Weath. Rev., p. 363, 1927]

No.	Amount precipi-tation	Chlo-rine	No.	Amount precipi-tation	Chlo-rine
18	12.0	0.71	21	6.0	17.04
23	6.0	120.7	24	3.0	77.39

Rain-profiles--Because of the complexity of the conditions it is difficult to arrive at reliable conclusions as to the composition of rain with respect to moisture-sources from considerations of storm-periods and water-losses. Better results can be obtained from a study of the chlorine-content of rain where such data are available. If their forms are not too much disturbed by orographic conditions it will be found that rain-profiles proceeding inland from the coast can often be quite accurately represented by an equation of the form

$$P = ae^{-k_1 x} + b(1 - e^{-k_2 x})$$

where P is the precipitation-depth, x the distance inland in miles, and k_1, k_2, a, and b are constants for a given profile. Figure 3 shows such a profile for the Hudson Valley. North of the mountain barrier at Storm King the profile follows the equation given by Figure 3 except for some topographic

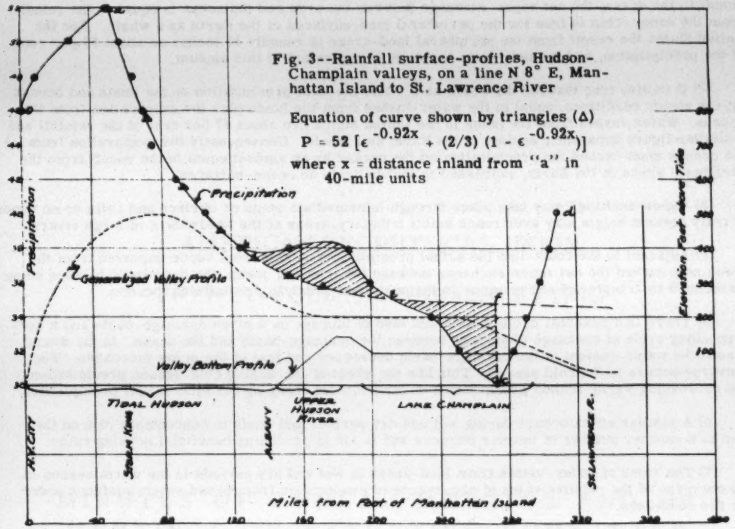

Fig. 3--Rainfall surface-profiles, Hudson-Champlain valleys, on a line N 8° E, Manhattan Island to St. Lawrence River

Equation of curve shown by triangles (Δ)

$$P = 52\,[\epsilon^{-0.92x} + (2/3)\,(1 - \epsilon^{-0.92x})]$$

where x = distance inland from "a" in 40-mile units

effects at the divide between the Hudson and Champlain valleys. The first term in the equation apparently represents precipitation from vapor derived from the ocean. The value of this term approaches zero as x increases. The second term in the equation apparently represents precipitation from vapor of inland origin and this term increases with x, approaching a limit b. In case of other rain-profiles the second or reprecipitation-term of the equation is often sensibly constant.

Determination of runoff from vapor-exchange--The quantity of runoff is almost wholly unknown for nearly all oceanic islands on the Earth and for a large portion of the areas of the continents. To determine the average runoff from an island like Madagascar, having over 20 large rivers entering the ocean and 2,000 miles of coast-line, with mostly direct drainage, would require years of observation and at many gaging-stations. It appears possible to determine approximately the runoff from an oceanic island from the simple fact that the average runoff is equal to the net vapor-exchange between the surrounding ocean and the island. Navigation-maps are available giving surface wind-directions and wind-velocities, temperatures, relative humidities, and other data from which the vapor-content of the air near the surface can be determined. While the method has apparently never been used, it appears possible, using known relations between the average vapor-content of a vertical air-column at different heights, and the vapor-content at the ground-surface, together with relations of average velocities and directions of wind at different heights to those at the surface, to determine the average inflow to and outflow of vapor to the atmosphere over a given island, month by month or for average conditions, and from these data to determine the net vapor-exchange and consequently the runoff. The accuracy of the result would depend on the accuracy with which known data for surface-conditions can be translated into average data for the air-prism up to the height--usually a few thousand feet at most--above which the vapor-content of the air becomes negligible. The computations involved in this arm-chair method of determining runoff would no doubt be laborious if carried out in detail but the method appears capable of giving results of the right order without the long delay which is unavoidable in determining average runoff by direct gagings.

Summary

(1) The storage-equation provides a basis for determining the net vapor-exchange between lands and oceans but not for determining the relative amounts of precipitation derived from moisture from different sources. For any land-area, large or small, coastal or inland, producing

runoff to the ocean, the net vapor-exchange between the area and the ocean is equal to the runoff from the area. This is true for the peripheral land-surfaces of the Earth as a whole. For the United States the runoff from the peripheral land-areas is roundly 11 inches or about 33 per cent of the precipitation, and the net vapor-exchange is equivalent to this amount.

(2) It is also true that for the world as a whole the total precipitation on the lands and oceans is, for steady conditions, equal to the water-losses from the lands plus the evaporation from the oceans. Water-losses from the lands in the United States are about 67 per cent of the rainfall and a similar figure apparently applies to the Earth as a whole. Consequently the evaporation from the oceans must exceed the precipitation on the oceans by an amount equal to the runoff from the peripheral areas of the Earth, expressed in inches depth on ocean-surfaces.

(3) Vapor-exchange may take place through intermediate steps or barters and little or no vapor of truly oceanic origin may ever reach small tributary-areas at the headwaters of large rivers.

(4) Adjacent to the coast-line the actual precipitation of rain from vapor imported from the ocean may exceed the net vapor-exchange between the land and ocean, the hydrologic balance being maintained by transfer of native vapor to the ocean and which is precipitated thereon.

(5) There is a seasonal cycle of gain and loss of storage on a given drainage-basin and a corresponding cycle of exchange of storage between the drainage-basin and the ocean. In the warm season the water-content of the drainage-basin decreases and that of the ocean increases. The converse occurs in the cold season. This has the effect of increasing cold-season precipitation and decreasing warm-season precipitation on land without changing the total annual precipitation.

(6) A similar effect occurs during wet and dry periods and tends to concentrate rain on the land in a smaller number of heavier showers and to aid in producing beneficial soaking rains.

(7) The rates of water-losses from land-areas in wet and dry periods in the warm season is the converse of the relative rates of occurrence of evaporation from broad water-surfaces under the two conditions.

(8) Light is thrown on the composition of rain in terms of vapor-sources from a consideration of the chlorine-content of rain and from the equations of rain-profiles proceeding inland from the coast.

(9) It appears to be possible to make an approximate determination of the runoff from a given area, such as an oceanic island, from a study of net vapor-transfer between the atmosphere above the area and the surrounding region.

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Voorheesville, New York

AMERICAN GEOPHYSICAL UNION

TWENTY-FOURTH ANNUAL MEETING

MINUTES OF ANNUAL MEETING AND OF MEETINGS OF EXECUTIVE COMMITTEE SECTION OF HYDROLOGY

Washington, D. C.
April 23 and 24, 1943

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MINUTES OF THE MEETING OF 1943
SECTION OF HYDROLOGY

(All sessions were held in Room 102 of the Hall of Government of the George Washington University, Washington, D. C.)

Morning Session, April 23, 1943

The first meeting was called to order at $09^h\ 30^m$ by Vice-President L. G. STRAUB. The scheduled session for business was postponed to $09^h\ 15^m$, April 25, 1943.

Reports of six Research-Committees, as printed in these Transactions [pp. 337-340, 341, 341-388, 339-401, 401-403, and 404-406], and of eight papers [pp. 425-438, 438-452, 452-460, 753-764, 460-465, 743-753, 465-467, and 468-475] were presented and discussed.

The meeting adjourned at $12^h\ 40^m$.

Afternoon Session, April 23, 1943

The second meeting was called to order at 14^h by Vice-President Straub, who introduced N. C. GROVER as Chairman for the session.

Reports of three Research-Committees [pp. 406-408, 408-409, and 409-421] and of nine papers [pp. 475-480, 480-487, 487-493, 498-500, 500-511, 511-524, 524-530, 536-547, and a paper entitled "Localized scour related to sediment-suspension" by B. T. MORRIS (publication of the last was postponed pending completion of manuscript)] were presented and discussed.

The meeting adjourned at $17^h\ 45^m$.

Morning Session, April 24, 1943

The third meeting was called to order at $09^h\ 15^m$ by Vice-President Straub, who introduced Past President L. K. SHERMAN as Chairman for the session. Following a brief business session the scientific program was resumed.

Reports of two Research-Committees [pp. 422-423 and 424] and eighteen papers [pp. 530-536, 547-564, 564-573, 573-580, a paper entitled "Graphical construction of hydrograph" by E. J. BEDNARSKI (not submitted for publication), 580-587, 587-594, 594-608, 609-618, 618-624, 624-632, 632-649, 651-693, 693-698, 699-719, 719-736, 736-737, and 737-742] were presented either in full, in abstract, or by title.

During the meeting WALDO E. SMITH spoke of the activities of the Union's Committee on Membership and the opportunities offered by membership and the need to acquaint well-qualified men engaged in the theory and application of scientific hydrology with these opportunities. J. J. DOLAND made some remarks concerning the summer meeting of the American Society of Civil Engineers at Los Angeles.

The meeting adjourned at $12^h\ 49^m$.

W. G. HOYT, Acting Secretary

Afternoon Session, April 24, 1943

A round-table discussion of papers presented was held beginning at 14^h, April 24, 1943, W. G. HOYT acting as Chairman for Vice-President Straub, who was in attendance at the General Meeting of the Union until $16^h\ 25^m$, when he relieved Mr. Hoyt. Some 35 Members took part in the discussions of papers and of matters pertinent to the welfare of the Section.

The paper on "The flood-hydrograph and valley-storage" by H N. TURNER [pp. 609-618] and the paper "On the plotting of flood-frequencies" by E. J GUMBEL [pp. 699-719] were discussed by Clark, Gumbel, Hertzler, Krimgold, Langbein, Merriam, Snyder, and others.

R. A. HERTZLER, Chairman of the Committee on Program, discussed the rules of the Section

for presentation of papers and requested that abstracts of all papers be prepared in accordance with these rules.

C. E. JACOB elaborated on his paper on "Correlation of ground-water levels and precipitation on Long Island, New York" [pp. 564-580].

A general discussion on ground-water phenomena followed. C. F. MERRIAM explained the studies in the Susquehanna River Basin on the relation between ground-water and runoff. C. F. IZZARD elaborated on the paper by himself and M. T. AUGUSTINE on "Analysis of runoff resulting from simulated rainfall on a paved plot." The paper was discussed by L. G. STRAUB, who presented his observations of flow-conditions and unusual hydraulic phenomena, especially regarding types of flow at shallow depths.

The session adjourned at $17^h\ 10^m$.

R. A. HERTZLER, Acting Secretary

APPENDIX A--MINUTES OF MEETINGS OF EXECUTIVE COMMITTEE OF THE SECTION OF HYDROLOGY DURING JANUARY TO JUNE, 1943

Members of Executive Committee--J. E. Church (President), L. G. Straub (Vice-President), K. H. Beij (Secretary), M. Bernard, R. A. Hertzler, R. E. Horton, W. G. Hoyt, G. W. Musgrave, L. K. Sherman, and L. K. Wenzel.

Summary of meetings of January 22, March 18, April 23, and June 28, 1943

Research-Committees--The Research-Committees and their functions, as expressed by their names, were established as follows: (1) Precipitation; (2) Snow; (3) Glaciers; (4) Evaporation; (5) Infiltration; (6) Physics of Soil-Moisture; (7) Runoff; (8) Dynamics of Streams; (9) Lakes; (10) Ground-Water; and (11) Chemistry of Natural Waters. A Sub-Committee, consisting of Bernard (Chairman), Hertzler, and Sherman, was appointed to study the problem of Research-Committees in its entirety, to define their constitution, functions, and aims, and to consider the desirability of additional Committees. As a result of the Sub-Committee's work there were established a Research-Committee on Land-Erosion, a Special Committee on Hydrologic Regions, and a Committee on Inter-Society Relations. The full report of the Sub-Committee is given in Appendix A-1.

Prizes and awards--A Sub-Committee, consisting of Musgrave (Chairman), Horton, and Wenzel, was appointed to study the advisability of awards for meritorious papers on hydrology in the Transactions. The report of the Sub-Committee is given in Appendix A-2. Final action by the Executive Committee was deferred indefinitely.

Regional Committees--A Sub-Committee, consisting of Sherman (Chairman), Hertzler, and Wenzel, was appointed to set up an outline of the function, organization, and powers of Regional Committees, and to study and clarify the relationship between the Section of Hydrology and the various Snow-Conferences. The report of the Sub-Committee is given in Appendix A-3. The Regional Meeting at Corvallis, Oregon, scheduled for June, 1943, was approved.

Glossary of hydrologic terms--A Sub-Committee consisting of Hoyt (Chairman), Drane, and Saville, was appointed to study the advisability of the preparation of a glossary of hydrologic terms. The work of the Sub-Committee is in progress.

Special Committees--R. A. Hertzler was appointed Chairman of the Committee on Program and L. K. Wenzel Chairman of the Committee on Publications. It was ordered that all papers from Regional Meetings be transmitted directly to the Committee on Publications for approval, and the Committee was authorized and instructed to hold all papers and discussions from all meetings until their content was approved, even if such procedure meant the postponement of publication of a paper or discussion until the following year.

K. H. BEIJ, Secretary,
Executive Committee, Section of Hydrology

APPENDIX A-1--REPORT OF SUB-COMMITTEE ON RESEARCH-COMMITTEES
(Distributed to all Chairmen of Research-Committees, June 30, 1943)

The following directive was given this Sub-Committee of the Executive Committee at its meeting of March 18, 1943:

"During the discussion relating to the Research-Committees, it was brought out that since the Section of Hydrology was created there have been numerous changes and additions in their number, functions, and alignment. It was the consensus of the Executive Committee that the time is ripe when the present functions of the eleven Research-Committees should be analyzed and attempt made to redefine their activities and aims. It was moved, seconded, and approved that Dr. Straub appoint a Sub-Committee of the Executive Committee to study the problem of Research-Committees in their entirety and report back to the Executive Committee at some future meeting. Vice-President Straub appointed Merrill Bernard as Chairman of this Sub-Committee, other members to be appointed later." (Leroy K. Sherman and R. A. Hertzler were later appointed.)

In accordance with this instruction the Sub-Committee submitted at the meeting of the Executive Committee on June 28, 1943, the "Statements of purpose" presented below. Please review that describing the scope of activity of your Committee, and suggest any change which will improve the accuracy of the statement without materially altering its form.

Attention is invited to the following "Statement of work to be done" which applies to all Committees:

Each Committee is to undertake (a) to stimulate research within its field, (b) obtain the preparation of papers of such a character as to advance the field of hydrology to which it is devoted, (c) secure coordination of workers and correlation of the results of research in different branches of its field, (d) facilitate dissemination of literature in its field, and (e) make an annual report which, so far as practicable, is to be presented at the Annual Meeting of the Union and published in its Transactions. It shall also be the duty of the Committee to examine into its relations with other Sections of the Union and with the several International Commissions.

Please return your approved or amended statement at an early date in order that the report of the Sub-Committee may be included in the Transactions of 1943.

MERRILL BERNARD (Chairman), R. A. HERTZLER, L. K. SHERMAN
Sub-Committee on Research-Committees

Statements of Purpose for Permanent Research-Committees

The scope of activity of the Committee on Precipitation embraces precipitated atmospheric moisture in the form of rain, snow, hail, and sleet. This field includes: Measurement; rain-drop characteristics; interception; storm-characteristics; regional distribution; relation to engineering and agricultural problems; and related research. The Committee will coordinate its work particularly with the Research-Committees on Snow, Evaporation and Transpiration, Infiltration, Runoff, and Land-Erosion, and with the Section of Meteorology.

The scope of activity of the Committee on Snow embraces snow after it is deposited on the ground. This field includes: Measurement of snow-depth, water-content, thermal quality, and structure; the phenomenon of melting; geographical distribution; influence on climate; and related research. The Committee will coordinate its work particularly with the Research-Committees on Precipitation, Evaporation and Transpiration, Infiltration, Runoff, and Glaciers, and with the Section of Meteorology and the International Commission on Snow and Glaciers.

The scope of activity of the Committee on Glaciers embraces the hydrology of existing glaciers as distinguished from ancient glaciers. This field includes: The systematic measurement and recording of current variations in volume of American glaciers; the interpretation of such variations; studies of structure, mode of movement, and regimen of glaciers; and related research. The Committee will coordinate its work particularly with that of the Research-Committees on Snow and on Lakes and with the International Commission of Snow and Glaciers.

The scope of activity of the Committee on Evaporation and Transpiration embraces the

processes of evaporation or sublimation from water, snow, land, and vegetal surfaces. This field includes: Measurement; theory; geographical variations; and related research. The Committee will coordinate its work particularly with that of the Research-Committees on Snow, Physics of Soil-Moisture, Infiltration, and Lakes.

The scope of activity of the Committee on Infiltration embraces the movement of water into the surface-soil. This field includes: Measurement of rates and volumes; the relation of soil- and rainfall-characteristics, vegetation, and topography to infiltration; geographical variations of physical processes; and related research. The Committee will coordinate its work particularly with that of the Research-Committees on Precipitation, Runoff, Physics of Soil-Moisture, and Chemistry of Natural Waters.

The scopy of activity of the Committee on the Physics of Soil-Moisture embraces the occurrence and movement of moisture within the soil or rock-mantle. This field includes: Measurement of rates and volumes; the dynamics of soil-moisture; the relation of soil-characteristics to moisture; the effect of vegetal roots on moisture; and related research. The Committee will coordinate its work particularly with that of the Research-Committees on Infiltration, Ground-Water Runoff, Erosion, Evaporation and Transpiration, and Chemistry of Natural Waters.

The scope of activity of the Committee on Runoff embraces water flowing over and through the ground or in channels. This field includes: Measurement of volume and rate of flow; characteristics of hydrographs; effects of natural and artificial storage; sources of supply to stream-flow, such as surface-runoff, subsurface- or base-flow; and related research. The Committee will coordinate its work particularly with that of the Research-Committees on Precipitation, Infiltration, Evaporation and Transpiration, Physics of Soil-Moisture, Ground-Water, Land-Erosion, and Dynamics of Streams.

The scope of activity of the Committee on Dynamics of Streams embraces the dynamics of the flow of water in streams and the relation between streams and the channels they occupy. This field includes: The forces which the water exerts; the work done in eroding, transporting, and depositing materials comprising the channel; and related research. The Committee will coordinate its work particularly with that of the Research-Committees on Land-Erosion, Runoff, and Chemistry of Natural Waters, and also with that of the Committee on Sedimentation of the National Research Council and of the Section of Oceanography.

The scope of activity of the Committee on Lakes embraces water occurring in natural or artificial lakes. This field includes: Measurements of surface-elevations, distribution of temperature, seepage-losses, and densities; ice-formations; seiches; sedimentation; origin; and related research. The Committee will coordinate its work particularly with that of the Research-Committees on Precipitation, Runoff, Ground-Water, Glaciers, and Chemistry of Natural Waters.

The scope of activity of the Committee on Ground-Water embraces the occurrence and movement of water in the zone of saturation. This field includes: Measurement of head and rate of movement, determination of the physical properties of water-bearing materials, and origin and sources of supply; geologic occurrence; geographical distribution; effects of pumping and other processes of artificial removal; natural discharge, chemical character, and theory; and related research. The Committee will coordinate its work particularly with that of the Research-Committees on Infiltration, Physics of Soil-Moisture, Runoff, Lakes, Chemistry of Natural Waters, and Evaporation and Transpiration.

The scope of activity of the Committee on the Chemistry of Natural Waters embraces the chemical composition and chemical work of natural waters, above and below the surface, except ocean water. This field includes: Development of sampling techniques; the relation between fresh- and salt-water; precipitates affecting infiltration, erosion, or water-movement; formation of subterranean channels; and related research. The Committee will coordinate its work particularly with that of the Research-Committees on Ground-Water, Lakes, Dynamics of Streams, Land-Erosion, and Infiltration, and of the Section of Oceanography.

The Executive Committee of the Section of Hydrology at a meeting held June 28, 1943, approved the formation of a new Research-Committee on Land-Erosion. The scope of activity of the Committee on Land-Erosion embraces the hydrologic aspects of the displacement of soil from its natural position in the soil-profile, as distinguished from the geological aspects of erosion. This field includes: Measurement of rate and volume; theory; the effect of alternate freezing and thawing; the effect of precipitation and snow-melt; the effect of vegetation and agricultural practices; and related research. The Committee will coordinate its work with that of the Research-

Committees on Precipitation, Snow, Infiltration, Runoff, Physics of Soil-Moisture, and Chemistry of Natural Waters.

The appointment of a Special Committee on Hydrologic Regions and of an Administrative Committee on Inter-Society Relations is recommended.

The objective of the Special Committee on Hydrologic Regions is to define regions of hydrologic similarity within the United States. The duties are: To coordinate past and present endeavors having similar or related objectives; to stimulate interest in defining areas of hydrologic similarity; to formulate and disseminate the needs for such definition; and to make recommendations and prepare reports of findings and progress for publication in the Transactions.

The members of the Administrative Committee on Inter-Society Relations shall be members of the Section of Hydrology and in addition have individual membership in selected organizations with which, through mutual consent, there shall be continuing cooperative relations. It shall be the function of this Committee: To keep the Research-Committees of the Section, and respective committees of the cooperating organizations, informed on the work in progress; to call attention to duplication; to facilitate the interchange of pertinent material of mutual interest; to encourage coordination and collaboration; and to make an annual report to the Executive Committee.

APPENDIX A-2--REPORT OF SUB-COMMITTEE ON PRIZES AND AWARDS (June 28, 1943)

This report of the Sub-Committee on Prizes and Awards, which presumably is its final report, is intended to be a factual presentation of the situation upon the basis of which the Executive Committee of the Section may determine upon its proper course of action. The Committee itself makes no formal recommendations.

The proposition of arranging an organized system of awards for papers submitted to the Section of Hydrology has, like many other propositions, several angles from which it may be viewed. From the viewpoint of the Section a well-organized system of awards doubtless would (a) stimulate in general greater care in the preparation of manuscripts, (b) raise the average level of quality in papers of the Section, (c) stimulate more papers from certain groups of workers (depending upon the desires of the Executive Committee and the specific plans which it formulated), and (d) have some advertising value in connection with expansion of membership. In addition to these effects there are numerous minor ones with which all are familiar and which, for lack of space, need no mention here.

Viewing the matter from another angle, the financial situation of the Union is far from stabilized and the burden which is being placed upon the General Secretary and Editor of the Transactions is extremely arduous. The Section of Hydrology a year ago in a round-table action agreed to make contributions annually, the sum of which would be assigned to the Special Fund of the Union to assist in securing the more definitely stabilized financial program now so long planned for the Union as a whole. Before completing this self-allotted assignment, we are considering embarking upon a second objective which is clearly of lesser importance to the welfare of the organization.

In other words, while it has been agreed that the Union can no longer operate through purely voluntary efforts and that provision must be made at an early date for at least a paid editor of the Union, nevertheless little tangible progress has been made in that direction. A stabilized organization should logically have first-order priority.

There are numerous other factors that deserve consideration. These are largely in the category of details to be worked out should it be decided to establish awards. For example, some societies have accepted endowments wherein limitations set forth later proved to be quite unfortunate. In one national society only three members were eligible under the prescribed limitations of one of the more important awards. Also some collaboration with other Sections would seem to be in order so that similar policies would prevail in general throughout the Union.

The Committee has canvassed the situation far enough to assure itself that a system of awards could be financed and it has agreed such a system would doubtless stimulate improvement in the quality of the papers of the Section. Undoubtedly at some future time, if not at present, a series of awards for outstanding papers would be a very desirable procedure to adopt.

Whether or not it is wise, however, to adopt such a policy at this time is a matter which deserves the careful consideration of the Executive Committee of this Section. If that Committee approved, the correct procedure then would be to submit the plan to the Executive Committee of the Union for its approval or disapproval.

G. W. MUSGRAVE (Chairman), R. E. HORTON, L. K. WENZEL
Sub-Committee on Prizes and Awards

APPENDIX A-3--REPORT OF SUB-COMMITTEE ON REGIONAL MEETINGS (June 23, 1943)

The Sub-Committee on Regional Meetings presents its report in two parts. Part I is information and comment on the development and activities of the Regional Meetings to date. Part II contains the Sub-Committee's recommendations as to the organization and operating procedures now to be adopted.

Part I--Information and Record

(1) The following abstract from the Statutes of the Section of Hydrology of the American Geophysical Union are presented here for reference.

"Article III--In addition to the annual meeting, other meetings of the Section of Hydrology may be held within certain regions designated by the Executive Committee. A Committee for each designated region shall be appointed. It shall be the duty of this Regional Committee to determine the time and place of meetings and to supervise the programs thereof. Papers presented at Regional Meetings shall be received subject to the publication requirements of the Section. Chairmen and members of Regional Committees shall be appointed in the manner specified in Article II relating to Research-Committees."

(1a) For a comprehensive statement relating to Regional Meetings, see paper by Dr. J. E. CHURCH, Activities of the Section of Hydrology" [Trans. Amer. Geophys. Union, p. 510, 1937].

(2) Comments on Regional Meetings--The extension of Regional Meetings and Areas is due to the interest and work of Dr. Church during his term as Vice-President of the Section of Hydrology, 1937-39. The procedures stated by Dr. Church received the approval and support of the then Executive Committee, Section of Hydrology. It was realized that the Far West had many Members of the American Geophysical Union and the Section of Hydrology, that the great distance from Washington, D. C., prevented many of them from attending the Annual Meetings, and, of major importance, that unless a local forum of Members of the Union was provided, a separated and uncorrelated Western organization on hydrology would probably be formed.

In the initial formation for Regional Meetings of the Section of Hydrology and in the cooperative arrangement with the Western Interstate Snow-Conference for publication of their papers in the Transactions of the Union, the Executive Committee made no hard and fast rules in advance. It was realized that an experiment was being made and that the best ultimate procedures were in a process of evolution.

(3) Two types of Regional Meetings have been held: (a) Meetings sponsored by a Regional Committee of the Section of Hydrology alone; and (b) meetings where the Western Interstate Snow-Conference also presented its own program under its own officers. Members from both groups attended each other's programs and discussions.

(4) There are also meetings on scientific or applied hydrology primarily sponsored by a University or College in which the Section of Hydrology of the Union participated together with representatives of several other organizations. The papers presented at these meetings were published by the sponsoring University or College after it had made a canvass of the paying subscribers.

(4a) Regional Meetings have been held during June, 1934, to June, 1943, as shown by Table 1.

Table 1--List of Regional Meetings, 1934-43

No.	Place	Date	Region[a]	Transactions	
				Year	Pages
1[b]	Berkeley, California	June 20, 21, 1934	(2)	1934-II	522-633
2[b]	Pasadena, California	Jan. 31, Feb. 1, 1936	(2)	1936-II	455-562
3[c]	Denver, Colorado	June 21-26, 1937	(4)	1937-II	510-663
				1938-II	668-669
4[d]	Spokane, Washington	Dec. 28, 29, 1937	(3)	1938-II	589-594
5[b]	Davis, California	Jan. 7, 8, 1938	(2)	1938-II	595-667
					671-744
6[b]	Los Angeles, California	Dec. 16, 17, 1938	(2)	1939-I	1- 96
7[b]	Spokane, Washington	Dec. 28, 1938	(3)	1939-I	97-138
8[e]	Richmond, Virginia	Dec. 27, 1938	...	1940-III	781-826
9[f]	Columbus, Ohio	Dec. 29, 1938	...	1940-IV	1065-1146
10[b]	Stanford University, California	Jan. 12, 13, 1940	(2)	1940-I	5-143
11[g]	Seattle, Washington	June 19-22, 1940	(1), (3)	1940-III	832-1061
12[b]	Sacramento, California	Jan. 16, 17, 1941	(2)	1941-I	1-216
13[e]	Dallas, Texas	Dec. 30, 1941	...	1942-I	3- 56
14[b]	Pasadena, California	Jan. 16, 17, 1942	(2)	1942-I	57-168
15[b]	Corvallis, Oregon	June 16, 1943	(1)	1943-III	1-102

[a]For designation of Regional Areas see page 774.

[b]Jointly with Western Interstate Snow-Conference.

[c]Jointly with American Association for Advancement of Science and Western Interstate Snow-Conference; for papers in a symposium on watershed management see Journal of Forestry, v. 35, pp. 991-1055, 1937.

[d]Jointly with Northwest Scientific Association; for other papers see Northwest Science, v. 12, p. 26, 1938.

[e]Jointly with American Association for Advancement of Science.

[f]Jointly with American Association for Advancement of Science, American Mathematical Society, Mathematical Association of America, and Geological Society of America.

[g]Jointly with American Association for Advancement of Science and Western Interstate Snow-Conference.

(4b) In addition, Members of the Section of Hydrology of the Union participated in conferences held under the auspices of State Universities or Colleges as shown in Table 2.

Table 2--Conferences participated in by Section of Hydrology of the American Geophysical Union

Place and year	Subject	Published in
Iowa City, Iowa, 1939	Hydraulic and Hydrology Conference	Proceedings, Iowa State University
State College, Pennsylvania, June 30-July 2, 1941	Hydrology Conference	Proceedings, Pennsylvania State College (270 pp.)
East Lansing, Michigan, December 10-12, 1941	Central Snow-Conference	Proceedings, Michigan State College (214 pp.)

(4c) Some Regional Meetings of the Section of Hydrology of the Union have been held purposely at the same date and in the same city as a meeting called by some other agency, such as the American Association for the Advancement of Science. Our Denver Meeting is an example. Although the places of meeting were separate and although there was little or no attempt at correlation, mutual benefit in the numbers attending the meeting was evident.

(5) The Western Interstate Snow-Conference--The meetings of the Western Interstate Snow-Conference have generally been held at the same places and during the same periods as the Section's Regional Meetings.

(5a) At a business meeting of the Western Interstate Snow-Conference, affiliation with the Section of Hydrology was discussed. It was decided that the Snow-Conference would not be an affiliate but would continue as a separate cooperating organization [Trans. Amer. Geophys. Union, Part III, pp. 90-92, 1943]. The Western Interstate Snow-Conference is therefore a sister organization with many interests in common with the Committee on Snow of the Section of Hydrology. The two organizations, however, are entirely distinct.

(5b) The papers and proceedings of the Western Interstate Snow-Conference have been published in the Transactions of the Union. This was at first conditioned on the payment by the Western Interstate Snow-Conference to the Union of the cost of publication and later only of cost of reprints.

The Western Interstate Snow-Conference until recently had no dues for membership. The funds for publication have been mainly derived by subscriptions for reprints and funds furnished by member organizations, both public and private, of the Snow-Conference. In most instances, Dr. Church has shouldered the onerous responsibility of collecting the funds for publication. Frequently he has personally advanced publication funds to the Union and Dr. Fleming has also helped in the same way. The Western Interstate Snow-Conference now has dues of $1.00 per year which may help the situation some.

(5c) The abstracting and editing of papers submitted by the Western Interstate Snow-Conference has been done largely by Dr. Church, Dr. Fleming, Mr. Capello, and Secretary Elges of the Snow-Conference. Papers presented by the Snow-Conference in the past have not always been presented to the Committee on Publications of the Section of Hydrology of the Union. (For change recommended see Part II.)

A review of the papers from the Snow-Conference as published in the Transactions of the Union indicates that most of these papers are of the same high scientific quality as those presented by the Section of Hydrology and other Sections of the Union. Some papers from the Snow-Conference, having little relation to the science of hydrology, would have been rejected by the Committee on Publications of the Section of Hydrology.

(5d) The Sub-Committee on Regional Meetings offers the following comments on hydrologic papers: The principal reasons for the formation of the Section of Hydrology of the American Geophysical Union was the lack of a forum for the consideration of purely scientific phases of hydrology and the lack of a medium which would accept papers of a purely scientific nature. Mediums of publication for applied hydrology and engineering do and have existed for a long time. There is no occasion for the American Geophysical Union to duplicate this field.

Sharp demarkation between the realms of pure and applied hydrology is difficult and generally undesirable. The American Society of Civil Engineers has a Committee on Hydrology. So has the American Society of Agricultural Engineers. Both of them are doing excellent work in scientific hydrology relating to their own fields. The ultimate use of pure science is in its application for the betterment of mankind. Many phases of science can be simplified by illustrations of use and applications. Papers of the American Geophysical Union can pertinently show the relation between applications and science. When the paper omits the scientific approach, it is not in the field of the Union.

(5e) The Central Snow-Conference was given permission to affiliate with the Section of Hydrology of the American Geophysical Union at the Section's business meeting in Washington, D. C., in 1940. The Proceedings of the Central Snow-Conference at East Lansing [p. 213] contain a report of its Special Committee recommending "that the Central Snow-Conference affiliate with the American Geophysical Union in a manner acceptable to the American Geophysical Union." (No further action.)

(5f) Regional Areas at the present time are:

(1) North Pacific Coast Area, which includes the States of Washington (Central and Western sections) and Oregon.
(2) South Pacific Coast Area, which includes the States of California, Nevada, and Arizona.
(3) North Continental Divide Area, which includes Eastern Washington, Idaho, and Montana.
(4) South Continental Divide Area, which includes Utah, Wyoming, Colorado, and New Mexico.

(Note: Territory north of the United States border, as noted in Dr. Church's paper in Transactions of 1937, is not included here on account of conflict with Article 2 on Membership of the Statutes and By-Laws of the American Geophysical Union.)

(5g) The cost of publishing the papers presented at Regional Meetings of the Section of Hydrology in the Transactions is now borne by the American Geophysical Union.

Part II--Findings and Recommendations of the Sub-Committee on Regional Meetings

(1) The value of Regional Meetings of the Section of Hydrology of the American Geophysical Union has been demonstrated. At the present time, there is need for a better correlation between the activities of the Regional Committees and the Executive Committee and its agencies in the Section of Hydrology.

(2) The papers on hydrology, published in the Transactions of the Union, represent the views and findings of the authors. The character and quality of these papers represent, or should represent, the approval of the Committee on Publications of the Section of Hydrology and its supporting opinions from the Research-Committees of the Section.

(3) The Sub-Committee recommends that no papers on hydrology be published in the Transactions of the Union without bearing the approval of the Committee on Publications of the Section of Hydrology.

(4) New Regional Areas--The Sub-Committee recommends that it be the policy of the Executive Committee of the Section of Hydrology of the Union to create further Regional Areas, with Regional Committees, for the purpose of sponsoring Regional Meetings of the Section of Hydrology or of cooperating with other agencies in sponsoring such conventions.

It is recommended at the present time that two new main Regional Areas be established, namely:

The Central Regional Area to include that part of the United States east of Regional Areas (3) and (4) and west of the east boundaries of Michigan, Indiana, Kentucky, Tennessee, and Mississippi.

The Eastern Regional Area to include all that part of the United States east of the Central Regional Area.

(5) It is also recommended that the Central Regional Area be now subdivided into four parts designated as Regional Areas (5) to (8) and that the Eastern Regional Area be subdivided into three parts designated as Regional Areas (9), (10), and (11).

(6) Regional Chairmen--As and when conditions warrant, the President shall appoint, with the approval of the Executive Committee, Chairmen for each or any one of the aforesaid eleven Regional Areas. It shall be the duty of each Regional Chairman, assisted by a local committee of his selection, to perform the following:

(a) To note and report favorable opportunities for meetings or conferences on hydrology to be held within his Regional Area.

(b) To act in cooperation with the Chairman of the General Sub-Committee [see paragraph (7)] in the selection of the time and place for holding a Regional Meeting, to supervise and arrange programs of his Regional Meetings, to receive all papers and written discussions presented at his Regional Meetings, to transmit such papers, together with his comments, to the Chairman of the General Sub-Committee.

(c) To cultivate friendly and cooperative relations between the American Geophysical Union and all Colleges and other agencies within his Regional Area interested in hydrology.

(7) General Sub-Committee on Regional Meetings--The President shall appoint a General Sub-Committee on Regional Meetings of three members of the Executive Committee. It shall be the duty of this General Sub-Committee to assist each Regional Chairman and his Regional Committees in performing their duties and to correlate the activities of Regional Meetings with the Executive Committee, Section of Hydrology of the Union. The Chairman of this General Sub-Committee shall receive from the Regional Chairmen all papers and written discussions presented at Regional Meetings. He shall transmit all such papers to the Chairman of the Committee on Publications of the Section of Hydrology for editing, revising, rejection, or publication in the Transactions.

(8) American Geophysical Union liaison--One member of the General Sub-Committee shall be designated to keep closely in touch with the General Secretary of the American Geophysical Union with regard to plans and arrangements for Regional Meetings in order that the Executive Committee of the American Geophysical Union may have prompt and prior information as well as opportunity to consider such matters from the point of view of policy and expense.

It shall be the responsibility of the General Sub-Committee [see paragraph (7)] to make and approve, with the General Secretary of the American Geophysical Union, any arrangements for the publication in the Transactions of any papers submitted by agencies outside of the American Geophysical Union.

The General Sub-Committee [see paragraph (7)] of the Section of Hydrology of the American Geophysical Union shall be responsible for the collection of funds from outside agencies to pay for the cost of publication of their papers.

L. K. SHERMAN (Chairman), R. A. HERTZLER, L. K. WENZEL
Sub-Committee on Regional Meetings

APPENDIX A-4--NEW YEAR LETTER TO THE MEMBERSHIP OF THE SECTION OF HYDROLOGY OF THE AMERICAN GEOPHYSICAL UNION (April 7, 1943)

This message is novel but essential to solidarity in these days of diversion of colleagues to the protection of human ideals.

The American Geophysical Union under the continuing leadership of Dr. Fleming, General Secretary, is determined to move forward to broader fields, larger membership, and increased research activity. The Section of Hydrology now in its new triennium shares this determination.

To maintain the spirit of conference and self-direction, an Executive Committee of ten members has been formed, a majority of whom reside in the District of Columbia. To supervise various details, administrative, research, and special committees have been formed. To bring the Section of Hydrology to the Members, a series of Regional Areas has been proposed in which meetings can be held on regional or national themes as they long have been in the West.

The personnel of the Executive Committee is a geographic and administrative cross-section of the Membership:

J. E. Church, President (Nevada)
Lorenz G. Straub, Vice-President (Minnesota)
K. Hilding Beij, Secretary (District of Columbia), Bibliography
Le Roy K. Sherman (Chicago), Regional Meetings
George W. Musgrave (District of Columbia), Membership
R. A. Hertzler (District of Columbia), Program
L. K. Wenzel (District of Columbia), Publications
Robert E. Horton (New York)
Merrill Bernard (District of Columbia)
W. G. Hoyt (District of Columbia)

The Research-Committees have been arranged on the following pattern to indicate the opportunities for cooperation of Committees and their position in the hydrologic cycle:

Precipitation, Merrill Bernard
Snow, J. E. Church and W. U. Garstka
Glaciers, François E. Matthes
Evaporation and Transpiration, H. G. Wilm
assisted by C. W. Thornthwaite
Infiltration, G. W. Musgrave
Physics of Soil-Moisture, F. J. Veihmeyer
Runoff, W. G. Hoyt
Dynamics of Streams, L. G. Straub
Lakes, S. T. Harding
Ground-Water, S. W. Lohman
Chemistry of Natural Waters, C. S. Howard

Since the Committees have been developing independently for the past decade, the Executive Committee desires to analyze them for further adjustments.

Under consideration also are two Special Committees on Erosion and Coordination. Both represent a desire for broader viewpoint, the former from water to air erosion and the latter from the single Society of Agricultural Engineers to all societies in pure and applied hydrology. The Committee on Erosion has long been desired by President LOWDERMILK of the American Geophysical Union, who is now assisting China in reestablishing irrigation. He also has urged the search for more centers for hydrologic research.

Because of the present restriction on meetings the Committees must now become the center

of communication for their various fields. Their annual reports should accordingly be "year books" of progress with detailed summaries of research and outlines of plans. Bibliographies of current publications--now few but correspondingly valuable--should be appended. To facilitate correspondence, the personnel of Committees should be published.

To offset the enforced inactivity of the International Commissions in Hydrology, the Committees of the Section have expanded their interest to include the Western Hemisphere and in keeping with the admission of neighboring nationals to Membership in the Union have invited representatives from all the Americas to share their work. The Committees on Snow and on Glaciers have long had such associates and the Committees on Precipitation and on Ground-Water have adopted the practice. The last-named Committee has an unfolding opportunity to aid in the problem of municipal water-supply and sanitation in the far South. President Lütschg of the International Association of Scientific Hydrology has written that he will call a hydrologic conference immediately at the close of the war to restore the upswing so suddenly terminated at Washington in 1939 by hostilities.

Meetings at Salt Lake City, Bloomington (Illinois), and Berkeley have been planned but deferred because of restrictions of travel and preoccupation with war. Two meetings, however, will be held: The Annual Meeting at Washington, April 23-24, and the Regional Meeting at Corvallis, Oregon, June 16.

As so cogently expressed by Dr. CHARLES F. BROOKS, Director of Blue Hill Meteorological Observatory, "I am sure the Annual Meeting will be exceedingly well attended even if nobody but scientists in Washington should go. Nevertheless, there will certainly be some from outside who will be able to get away. As you intimate, the people in Washington are from so widely scattered sections of the country that even though the attendance might appear to be local its effects with respect to spreading knowledge through the country would be the same as though the men actually came from far places at the time."

The meeting at Corvallis of the Section and the Western Snow-Conference will be devoted to problems bearing on the winning of the war.

It is realized that both meetings should be local and that the general Membership can not and should not attend. For this reason contributed papers for presentation by title or summary at the Meeting or printing in the Transactions will be welcome. Discussions will be sought for all papers. To further the effort toward quality, the Executive Committee is considering the feasibility of offering "prizes or awards for meritorious papers on hydrology that are published in the Transactions of the Union."

Two immediate problems lie before us: (1) Increasing the Membership for mutual encouragement and strength in geophysical sciences; and (2) increasing the funds essential to maintaining the publications of the American Geophysical Union. The inevitable but fortunate result of the direct presentation of papers for printing will be the American Geophysical Journal ardently sought by General Secretary Fleming.

Chairman Musgrave of the Committee on Membership of the Union has done remarkable work in obtaining new Members. The Section of Hydrology, because of the great public interest in surface- and ground-water, has the greatest opportunity to aid. Potential Members are numerous, and personal solicitation effective.

Support for the Special Fund to place the Union on a better financial basis will come from contributing organizations in proportion to the personal contributions from the Members. Suggestions have been many that the annual dues be raised to $5. This may be desirable after the new Members have realized the values of the Union, but the opportunity for the older Members to make voluntary contribution of $1 or $2 each, even for one year, is at hand.

These projects of Membership and Special Fund have been centered on the Union by the Sections but could more successfully be carried through by them because of greater familiarity with colleagues. The problem is individual.

Two of our Members have died during the winter: David G. Thompson, long the Chairman of the Committee on Ground-Water; and Dr. Max Demorest, specialist in glacier-flow. Only in the lapse of time can their place be taken. Max Demorest died amid the Greenland ice in war service.

In these days of world horizons and international cooperation, it seems fitting to enclose with this letter some reflections on our distant comrades and the longed-for fruits of their victory.

Reno, Nevada

J. E. CHURCH, President,
Section of Hydrology

ERRATA

TRANSACTIONS OF 1943

Part I, cover
For "April 23, 24, and 25, 1943" read "April 23 and 24, 1943."

Part I, page 60
The dot was omitted from the right member of equation (1), which should read

$$du^v \propto v^u du \cdot$$

Part III, following page 102
The enclosed addendum giving discussions of papers at Corvallis, manuscripts for which had been misplaced, should be added to Part III.

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ADDITIONAL DISCUSSIONS AT CORVALLIS MEETING

(Lost in files of Editorial Committee of the Section of Hydrology and not submitted by that Committee until after completion of Part III)

Paper on "Stream-flow forecasting by pattern-behavior" by Rolla H. Wahle [Trans. Amer. Geophys. Union, Part III, pp. 13-28, 1943].

ROLLA H. WAHLE (closure)--As to consideration of the method on streams principally rain-fed, and trial where snow is not a large factor, I may say this is the first time it has been tried anywhere, but since starting work on this about two years and a half ago, I understand that some other gentlemen have done work along this same line. The only stream where we carried on such work is the Columbia.

As regards success of the method on account of the presence of snow, I regard what Mr. McLAUGHLIN had to say about snow-measuring as extremely interesting. I know that it is, of course, of great value, but I am not sufficiently acquainted with the methods, or the results up to the present time, to have any direct proof. I hope to have before too long and then I may be able to answer.

Our records indicate a direct connection between the first six months and the second. There might be one phase of runoff-factors creating runoff in one period, and in a similar period it would be another phase of these factors that would create the runoff. A certain runoff during the initial six-month period indicates a similar balance of flow-factors that entered into it. One year it might be a rain that would bring a peak, another time a lack of rain would make flood-indications less ominous. I would think, by my studies up to the present time, that the first six-month flow is indicative of the last six-month flow in many instances. There are probably many departures from pattern-groups, and if we had a record of the river for several hundred years we might determine departures.

Paper on "Some accomplishments in snow-surveying" by W. W. McLaughlin [Trans. Amer. Geophys. Union, Part III, pp. 38-43, 1943].

ASHTON CODD (Hydrologic Engineer, United States Weather Bureau Regional Office, Seattle, Washington)--Mr. McLAUGHLIN has mentioned many factors that enter into the complex problem of river-forecasting from snow-fed streams. In the day-to-day river-forecasting of rivers that rise in basins, which are partially or totally covered by snow, we find depth, water-content, and density do not give a complete picture of how much water will be released to runoff during a specific period of time. The quality of snow has a great deal to do with this particular problem and may be used as an index to snow-melt. Messrs. MERRILL BERNARD, WALTER T. WILSON, and PHILLIP LIGHT of the Weather Bureau Hydrometeorological Section in Washington, D. C., have presented some well-founded procedures and theories for coping with the snow-melt problem.

We in the Northwest are planning on carrying those procedures into the field for an actual trial and endeavor to apply the snow-quality measurements to river-forecasting. The snow-line elevation will also be observed to give a basis for computing that portion of the basin contributing to runoff or that area between the elevation of the snow-line and the elevation of the isotherm for 32°F.

Referring to Mr. CANFIELD'S question, the quality of snow may be defined as the ratio of the heat of melting of snow to the heat of fusion of pure ice. In a snow-pack there is a certain amount of free water. As soon as the snow melts, this water is liberated to runoff without requiring additional heat to change it into a liquid state as is the case of the ice-particles of the snow-pack. For example, snow of 60 per cent ice and 40 per cent water has a quality of 60 per cent and a heat of melting of $0.60 \times 80 = 48$ cal/gr or $0.60 \times 144 = 86.4$ BTU/lb. The factor to be determined is the heat of melting by using a calorimeter.

JAMES C. MARR (Boise, Idaho)--An Army Air Corps crew which crashed in the wilds of central

Idaho last winter reached a snow-survey shelter-cabin with its beds and stores of food and fuel after almost superhuman endurance during several days' travel through deep snow, and were saved at some expense to snow-survey facilities. The food was padlocked in a room in the basement and could have been reached by breaking the lock. The weary aviators, however, chose the more difficult and destructive procedure of ripping up the floor of the cabin.

Snow-surveys made during the middle of March in some sections and of April in others would be desirable. Also a measurement during mid-February would be useful during years of light falls of snow. I believe we should plan to enlarge the snow-survey program in this manner when it becomes possible to do so.

Paper on "Precipitation-runoff relationships as a basis for water-supply forecasting" by George D. Clyde and R. A. Work [Trans. Amer. Geophys. Union, Part III, pp. 43-55, 1943].

J. E. CHURCH (Nevada Agricultural Experiment Station, Reno, Nevada)--May I give you statistics for the present year at Soda Springs, at the summit of the Sierra? It was one of those many survey points at which we try to determine the runoff of the streams both east and west from this watershed. The precipitation there from November through March was 141.8 per cent of normal (a bumper year if it had been cold) but the snow-cover at the end of that period was only 98.2 per cent of normal on April 1 and snow was scant at lower elevations.

The people were afraid they would have a dry season because they had no snow down where they had seen it before, and the snow-cover at the low level was so small in amount that the snow-line was very, very high. And the snow was so extremely dense that the season was advanced, according to the old timers "a full month." Corporal WILLIAMS was so in hopes that we might see one of those "bumper" years while he was stationed in the Sierra. Only rains and melting prevented.

Likewise, in the Humboldt Basin during the same season (1942-43) the precipitation for November to February was 137.6 per cent of normal but the snow-cover on March 1 was 91.5 per cent of the normal of March 1 and at low levels only 42.1 per cent. But the forecast based on the highest water-table of record was a probable runoff during March to July of 185 per cent. On June 15 the runoff had already attained 168 per cent of normal. The effect of the high precipitation is clouded by the water-table. In the Sierra the runoff has usually corresponded with the snow-cover.

Unfortunately the superabundance of water in the precipitation has prevented the comparison of records of precipitation-gages with those of snow-surveys as Mr. ALTER intended. A winter-long comparison of ten precipitation-gages and recorders at Soda Springs revealed a high degree of accuracy of snow-catch that should compare favorably with that of snow-surveying. Both methods are necessary and mutually supplementary. One determines the winter gross assets in snow and water, the other the net assets of the remnant snow-cover. The latter, because of its quantity and continuity of melting, strongly influences the stream-flow.

Paper on "Forecasting runoff for power from relatively low-level areas" by Harry Olsen and E. B. Price [Trans. Amer. Geophys. Union, Part III, pp. 55-62, 1943].

J. E. CHURCH (Nevada Agricultural Experiment Station, Reno, Nevada)--Is not the runoff of the previous season or series of seasons given considerable weight in choosing the modifying factor applied by the authors to their data of snow and precipitation when forecasting the probable runoff of the current season? It is one of the steadying factors in the lava-watersheds, such as the Klamath and Pit, that have a hold-over from one season to the next.

In granite or even alluvial watersheds, as the Kern and Humboldt of Nevada, the basin may drain out to a minimum of 3.1 or even 0.8 per cent of the annual normal in September while the lava-beds may maintain a minimum of 4.1 per cent. Or, expressed in terms of the major flow during March to July or April to July due primarily to snow-melt, the flow of the Klamath will be only 53.9 or 42.0 per cent of the annual as compared with the flow of 67.5 or 61.4 per cent in the Kern and 83.2 or 71.2 per cent in the Humboldt.

The lack of crest or evenness of monthly flow in the Klamath as compared with the others is shown in Table 1.

Table 1--Monthly percentage of normal runoff in varying types of watersheds

Month	Alluvial soil Humboldt (Nevada) Palisade	Granite soil Upper Kern (Kernville)	Lava Klamath (Spencer Bridge)
	pct	pct	pct
October	1.7	3.3	5.0
November	2.2	2.8	6.0
December	1.9	2.8	7.8
January	2.6	3.9	9.1
February	3.8	3.6	9.4
March	12.0	6.1	11.9
April	19.0	10.1	13.3
May	20.0	17.3	12.4
June	23.5	22.4	9.5
July	8.7	11.6	6.8
August	1.5	5.3	4.6
September	0.8	3.1	4.1
March to July	83.2	67.5	53.9
April to July	71.2	61.4	42.0

In the three watersheds, the alluvial seems least capable of accumulating and distributing its flow, yet through a series of three years, its water-table has been built up until the soil has diverted sufficient melt-water into the stream-channel to double the flow based on the snow-cover during March to July. A snow-cover of 91.5 per cent of the normal on March 1 is producing a runoff that has already (June 15, 1943) attained 168 per cent of normal and is forecasted at probably 185 per cent.

It seems probable also that the lava-storage of the Klamath Basin may be built up or diminished sufficiently by the fluctuation of the snow-cover or precipitation over a series of years to affect the seasonal flow. This phenomenon is steadier and longer continued than the priming of the soil by autumn rains.

A project akin to forecasting on the Klamath is the relationship between the snow-cover on Charleston Mountain in southern Nevada and the fluctuation in the artesian flow at its base.

ASHTON CODD (Hydrologic Engineer, United States Weather Bureau Regional Office, Seattle, Washington)--Messrs. PRICE and OLSEN have a very unique scheme with which to forecast the stream-flow in the upper Klamath River. With the data they have collected, it would seem that a definite correlation between the runoff-factor and antecedent conditions should exist, especially where they have computed the runoff-factor for past seasons and compared it with their estimated factor. A graph plotted with runoff against precipitation for October to December, or some combination of factors, may prove very helpful.

Paper on "A simple procedure for the day-to-day forecasting of runoff from snow-melt" by Ray K. Linsley, Jr. [Trans. Amer. Geophys. Union, Part III, pp. 62-67, 1943.]

ASHTON CODD (Hydrologic Engineer, United States Weather Bureau Regional Office, Seattle, Washington)--Mr. McLAUGHLIN'S suggestion on the elevation of the snow-line is very logical. An excellent record could be kept by the use of photography. However, the problem of forecasting on a day-to-day basis will require a daily service of observation similar to rainfall and river gage-stations.

National Research Council

AMERICAN GEOPHYSICAL UNION

TRANSACTIONS OF 1943

PART III

REPORTS AND PAPERS

JOINT REGIONAL MEETING
SECTION OF HYDROLOGY
WESTERN SNOW-CONFERENCE
CORVALLIS, OREGON
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PREFACE

The American Geophysical Union was established in 1919 as the American Committee of the International Union of Geodesy and Geophysics, and its Executive Committee on Geophysics of the National Research Council. The objects of the Union are to promote the study of problems concerned with the figure and physics of the Earth, to initiate and coordinate researches which depend upon international and national cooperation, and to provide for their scientific discussion and publication. In the accomplishment of these objects, the Union is divided into Sections following the plan of organization of the International Union of Geodesy and Geophysics. There are now eight Sections, namely, (a) Geodesy, (b) Seismology, (c) Meteorology, (d) Terrestrial Magnetism and Electricity, (e) Oceanography, (f) Volcanology, (g) Hydrology, and (h) Tectonophysics. A Section of Geophysical Chemistry was discontinued May 31, 1924, as the International Union had failed to provide such a Section. The Section of Hydrology was established November 15, 1930--matters pertaining to scientific hydrology referred to the American Geophysical Union had been previously looked after by special committees on Hydrology. The Section of Tectonophysics was established April 9, 1940, for the purpose of promoting and encouraging research of fundamental importance to our knowledge of Earth-structure not covered in any one of the other Sections of the Union.

General assemblies of the Union and meetings of its Sections for presentation and discussion of papers and symposia are held in Washington, D. C., each year. The first annual meetings were those of 1920. Following the formation of the Section of Hydrology, Regional Meetings have been held usually in joint sessions with other organizations having coordinated interests. For the purpose of such meetings, the Executive Committee of the Section of Hydrology designated selected Regional Areas and their territories, namely: North Continental Divide--Montana, Idaho, eastern Washington, Oregon, and Alberta (affiliated); South Continental Divide--Colorado, Wyoming, Utah, and New Mexico; North Pacific Coast--western Washington, Oregon, Alaska, and British Columbia (affiliated); South Pacific Coast--California, Nevada, Arizona, and Hawaii. Besides the Regional Meetings sponsored by the Section of Hydrology, the Union has also encouraged joint meetings with organizations and societies interested in the discussion of various aspects of the geophysical sciences.

Through 1942, 14 Regional Meetings have been held. The present volume, Part III of the Transactions of 1943, contains the papers of the Joint Regional Meeting of the Section of Hydrology of the American Geophysical Union with the Western Snow-Conference at Corvallis, Oregon, June 16, 1943. The details of the meeting at Corvallis were under the general charge of J. C. STEVENS as Chairman of the North Pacific Coast Area of the Section of Hydrology of the Union and of R. A. WORK as Chairman of the Pacific Coast Area of the Western Snow-Conference.

The general officers of the American Geophysical Union for the meetings reported upon in this volume were: President, W. C LOWDERMILK; Vice-President, L. H. ADAMS; General Secretary, J. A. FLEMING. Those for the Section of Hydrology of the Union were: President, J. E. CHURCH; Vice-President, L. G. STRAUB; Secretary, K. H. BEIJ.

The costs of publication for the transactions of the Regional Meeting contained in the present volume were provided by the American Geophysical Union. Assembly and preliminary editing of the manuscripts were made by J. E. CHURCH, FRED PAGET, and J. C. STEVENS. The final editing and preparation of master-copy for publication were done by J. A. FLEMING and J. J. CAPELLO of the American Geophysical Union. We are indebted to W. C. HENDRIX and to J. W. GREEN for the necessary redrawing and photographic work for publication. As in past years, the final master-copy was planographed by the Kirby Lithographic Company of Washington.

The papers and extended discussions of the present volume are ample evidence of the useful character of the field of hydrology in the current emergency.

J. A. FLEMING, General Secretary,
American Geophysical Union

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REPORTS AND PAPERS

REGIONAL MEETING, SECTION OF HYDROLOGY

AND WESTERN SNOW-CONFERENCE

CORVALLIS, OREGON, JUNE 16, 1943

HYDROLOGY'S PART IN THE WAR EFFORT

J. C. Stevens

This war caught the United States and the other allied nations in a most deplorable state of unpreparedness--just like the other war did 29 years ago. One generation seems to be a sufficient length of time in which to forget virtually all the lessons learned from one major holocaust. Between catastrophies we assiduously pursue our studies and carry on research about almost everything except how to meet the next one.

When these emergencies arise we are not always prepared to apply the knowledge we have to a solution of many of the problems with which we are faced because such knowledge has never been pointed heretofore in that particular direction.

To illustrate: The necessity for training millions of troops and of building cantonments, ordnance, and industrial plants came upon us like a thunderbolt that shocked us out of the smiling complacency into which we had so easily drifted.

A cantonment large enough to house and train some 50,000 men was hastily decided upon. Of course, there were many other cantonments just as hastily decided upon, but it seemed necessary to build this particular one in the State of Expediency largely because it was urgently demanded by Senator Bring-Home-The-Bacon. The sum of n million dollars was allotted. The ancient firm of "Buildem and Studiem Afterwards" was employed as the Architect-Engineer. The site was picked, farmers were shooed off their land. Barns, houses, corn cribs, granaries, windmills, fences were removed and the land cleared. Guard-fences and guard-houses were erected. Contractors moved in and started building headquarters for themselves, for the Government's staff, and for the staff of the Architect-Engineer.

It had been assumed all along that an abundant water-supply could be had from Deception Creek that flowed near the site. But as the buildings rose the waters fell. Somebody decided to investigate. While a standard gaging-station had never been installed on Deception Creek, there were in published records readily available a goodly number of individual measurements of flow near the site during low seasons. The belated study disclosed the sad fact that each year the flow faded out to practically nothing during the summer and that there were no storage-sites.

The obvious decision was immediately reached to drill a series of wells. Well-drillers began immediately and as the buildings continued to rise the hopes that water could be found also rose. But alas and alack! By the time the cantonment was over 50 per cent completed it was definitely proven that there was no water and moreover that none could be secured within any justifiable time at any cost. What to do? What they did do was to abandon the project in favor of another site 350 miles away where the prudent firm of "Studiem and Then Buildem" was employed as the Architect-Engineers.

Learning hydrology's part in that war effort cost millions of dollars but what was far more important was the billions of dollars' worth of time irrevocably lost. This example is not unique. Small wonder Lloyd George coined the phrase "Too little too late"

Then there's the story of the Great Unbeliever. A peace-time training post adjacent to Fortuitous Ocean, with accommodations for a couple of regiments, was to be expanded into a 40,000-man cantonment in a great hurry. Captain Hipressure was promoted to Major and made the Constructing Quartermaster. It was open season on all the engineers, architects, contractors, material salesmen near and far. All the adjacent brush-studded rolling sand-hills and verdant valleys were purchased. There were no surface-waters of consequence available, so a battery of well-drillers was employed to expand the old Post's two-well system on the valley side into a many-well system on the ocean side. Specifications for drilling and developing the wells took too

much time to prepare, so the orders were "drill 'em over yonder, boys, near the buildings; use your judgment, only get water." They got water--plenty, in plenty of wells.

Then a couple of the best producers went salty. The Great Mogul at Headquarters ordered Hydrology to the rescue, much to the chagrin and disgust of Major Hipressure. Hydrology recommended the abandonment of the ocean-side wells in favor of valley-side wells--longer pipe-lines, higher pumping lifts, of course. The Major'd be darned if he'd abandon perfectly good wells! What if a few did salt up and others fill up with sand? He had plenty anyway. No hydrologic cyclist could tell him how to run his camp. So nothing was done except to add a few reservoirs and put sand-traps in the water-mains.

Those were years of abundant water-supply and the ground-water, high on the valley side, kept the ocean water out of the remaining wells. A lucky break for the Major who by this time had been promoted to Lieutenant-Colonel and transferred with honors.

Soon came a season of scant supply. The valley ground-water dropped too low to form a barrier. One by one the remaining wells began to show symptoms of salt. The new Quartermaster at least had a plan. It was musty and moth-eaten, but was dragged forth. Well-drillers were again called in, handed a set of specifications for drilling and developing. An inspector was employed. Water was found above any likelihood of salt-water encroachment. The Major got away with it largely because no time was lost. The mere $300,000 squandered did not count in that war effort, but obviously Hydrology should have had the medals instead of the Great Unbeliever.

A more pleasing picture is presented in the great complex of services that Hydrology and its near relative Meteorology are rendering the war effort with most wholesome effects. Water in adequate quantities and of proper quality is indispensable. Domestic supplies must be available at all cost. Hydrology can usually give the answer and avoid wasting precious time and money, and generally does.

Hydrology has become a vital tool in the prosecution of the war. During such an emergency as we are in at present the phases of Hydrology that are most important to the industrial production of war equipment, food, and supplies must be emphasized to the temporary exclusion of the research phases that can be postponed until the more propitious opportunities of the post-war period.

Water-supply for hydroelectric plants, for industrial developments, for domestic water-supplies, in cities, airfields, cantonments, concentration-camps, can be far more effectively used if the science of Hydrology is brought to bear on the programming of those uses.

Industrial power in enormous quantities and at minimum cost is vitally necessary for the innumerable chemical and metallurgical processes as well as for the simpler basic manufacturing requirements that make up such a large part of our war effort. Such power is best supplied from hydroplants. It is a source that is not exhaustible, such as obtains in the case of fuels.

Irrigated agriculture is also an indispensable part of the war effort. In many localities it flourishes alongside of and is interwoven with larger hydroelectric systems. Each thrives or falters on the idiosyncrasies of the same water-sources.

Those sources can be used unwisely, the penalty being a curtailed output. Hydrology supplies the knowledge that makes for the maximum output from available supplies. The quantities available are accurately and quickly made known not only concurrently as the water flows but in mountainous drainage-basins well in advance of the flow. By means of winter snow-surveys the supply in snow-storage is ascertained long before the spring runoff begins. Power-plant operation, irrigation-usage, storage-reservoir regulation, can be wisely planned, to the end that the maximum number of kilowatt-hours and the maximum crop-value may be extracted from the available waters.

Man is prone to build his cities and locate his most important industrial developments in the path of potential floods. He nonchalantly encroaches on waterways with dikes and sea-walls, naively fills the river-channels with multitudinous bridge piers and unheedingly narrows its widths with bridge approaches and shipping facilities.

In the scramble to augment production for war, previous warnings are often forgotten and temporal expediency supplies the excuse.

When the rains descend and the floods come he calls loudly on the gods of Meteorology and

Hydrology to save him from disaster. They come lamely to his aid. They give him some inkling of what heights to expect and warn him at least a few hours in advance of the arrival and duration of flood-peaks.

If only man would learn from experiences and profit by them! If only he would ask Hydrology where it is safe to build and then build in the safety zones indicated! If only he could learn some respect for Ole Man River and give him room according to his strength! If only he would not emulate the one of whom Robert Browning wrote:

"Oh he who draws a circle premature,
Heedless of far gain,
Greedy for quick returns of profit, sure
Has made a bad bargain!"
The Grammarian's Funeral

This war will not last long. Rehabilitation of blighted areas, the construction of delayed facilities, and the conversion of industrial plants to peace-time production will demand a greater expansion of the practical aspects of Hydrology than Hydrology was able to give to this war effort: First, because Hydrology is an ever-growing science and, second, the value of its services to mankind is gaining greater recognition. The war taught many a skeptic what of value Hydrology can render if only given the opportunity.

Spalding Building,
Portland, Oregon

HYDROLOGY'S PART IN THE WAR EFFORT

Merrill Bernard

War and water on the African Front have been matters of relatively small amounts of the latter, laboriously distributed over great distances, under the difficulties imposed by active combat. War and water on the Home Front relate themselves less spectacularly, but with decided emphasis.

The past decade has witnessed a striking change in the Nation's attitude toward water. Devastation by flood is no longer considered the unavoidable result of an Act of God, and there is now a well-established national policy on flood-control. Much has been accomplished toward the ultimate reduction of flood-damage in those localities where social and economic justification can be made for the investment in flood-control works. Even in cases lacking these qualifications the damage-potential will be substantially reduced through a greater preparation-opportunity as modern flood-forecasting methods are placed in operation. Water-conservation has likewise evolved as a national responsibility, for which active policies and programs have been established.

Water is abundant in our country and we have used it wisely in bringing into production Western valleys which otherwise would never emerge from their desert state. Abundant water and land have meant abundant food in normal times. What of a future in which three-quarters of the Earth's population look hungrily toward our fertile, well-watered fields?

The American hydrologist has a vital part in helping to meet unprecedented demands on our water- and soil-resources. Concentrations of industrial war effort on the flood-plains of our great rivers must be protected from damage and interruption to production, with resort to every available means. Ground-water sources must still further be drawn upon in localities where depletion is already a serious problem. An overburdened system of transportation will insist that food be grown as near as possible to points of consumption or ports of embarkation. This, in some cases, will bring many acres into temporary production which, having no assurance of a continuing water-supply, must be returned to range or unproductiveness before populations are lulled into a false sense of security created by a fortuitous series of years of adequate rainfall or above-normal volumes of water stored in the snow-fields and reservoirs.

Other accomplishments to which hydrologic planning has been the key could be listed. Vast blocks of hydroelectric power, depending upon the hydrologist's assurances of adequate stream-flow, have been made available to industry within planning and construction periods that, four years ago, would have been considered ridiculous. The hydrologist has given valuable aid in the selection of equipment for mountain troops; his knowledge has been important to the designer of

air-fields; his opinions have had much to do with the design of snow-removal and other engineering equipment; and he is being called upon to interpret hydrologic data for the operational planner in foreign theaters of war, which more often than not, are meager and inconclusive.

Experience has taught the value of continuity of record in the modern use of hydrologic data. The broken record is branded as a "statistical outcast", never wholly regaining its reputation. Those who are engaged in gathering hydrologic data are making it their business to keep observational stations in operation in spite of the difficulties imposed by war. The Corps of Engineers, Geological Survey, Soil Conservation Service, Tennessee Valley Authority, Weather Bureau, and other organizations and individuals are active in safeguarding our sources of data. The Section of Hydrology of the American Geophysical Union has reacted to the stimulus of war, and rather than "hole-in for the duration", has undertaken an active campaign for new members.

Yes, the hydrologist is in war, as in peace, proving worthy of the important element assigned him--water.

U. S. Weather Bureau,
Washington, D. C.

DISCUSSION

GEORGE H. CANFIELD (District Engineer, United States Geological Survey, Portland, Oregon)--Although there may be no discussion at this time, I do not want this moment to pass without expressing appreciation for the very fine presentation by J. C. STEVENS and MERRILL BERNARD on the functions performed by hydrology in the war effort. When first I saw this subject on the program I appreciated the fact that careful thought and study would be required to show this relationship adequately, which we all realize, and in a forceful way which would be understood by the public. I believe the others present will agree with me that both speakers have handled this assignment in a very creditable manner.

Mr. BERNARD'S statement mentioned the importance of no break in continuity of basic hydrologic data during this war. I am particularly interested in this thought as the United States Geological Survey is obtaining basic data as regards river-flow. We have been hit rather hard by induction of our men into the armed services or by the calling to active duty of our employees who were Reserve Officers, but it has been my thought, and also that of State Engineer STRICKLIN, with whom we cooperate, that we endeavor to maintain existing stream-flow measuring stations throughout the war even though there might be a delay in the computations of the records thereat. That is a somewhat different policy than occurred during the first World War, when several gaging-stations were temporarily discontinued and continuity of record interrupted. We plan and hope to obtain continuous records without interruption during the present war.

ELMER FISHER (Unit Supervisor, United States Weather Bureau, Portland, Oregon)--At the present time there are 280 stations in Region No. 7 equipped with recording precipitation-gages. Our losses in this type of station due to observers quitting or moving out of the community for high-paying positions has been less than five per cent. In many cases we have been able to secure new observers. Three new stations have been established. Considerable effort has been put forth by Hydrologic Inspectors, Unit Personnel, and other interested Weather Bureau officials to encourage observers to improve chart-records and it is believed that we can report some progress.

IMPROVING STREAM-FLOW PREDICTIONS BY THE USE OF PAST RECORDS

C. H. Niederhof

Since 1926 the management of the International Power and Paper Company, Ltd., has been forecasting stream-flow for the Grand Lake Basin in western Newfoundland. (Appreciation is extended to ERIC HINTON of Bowater's, Newfoundland Pulp and Paper Mills, Ltd., for furnishing the data upon which this paper is based.) As the company operates its paper-mill at Corner Brook exclusively by hydroelectric power, it is interested in the magnitude of the spring-flood which produces the major portion of the annual stream-flow. Accordingly, predictions of flood-magnitudes have been obtained in the early spring of each year since 1928 by means of snow-surveys and precipitation-records. The predicted runoff each year consisted simply of the water-content of snow calculated from a snow-survey made about the middle of March, plus precipitation measured until the end of March, plus a constant average figure--based on past records--expressing the

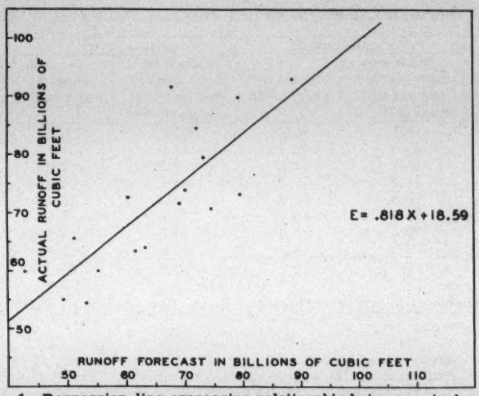

Fig. 1--Regression-line expressing relationship between actual and forecast runoff, in billions of cubic feet, based on snow-survey and precipitation records for the period 1928 to 1935

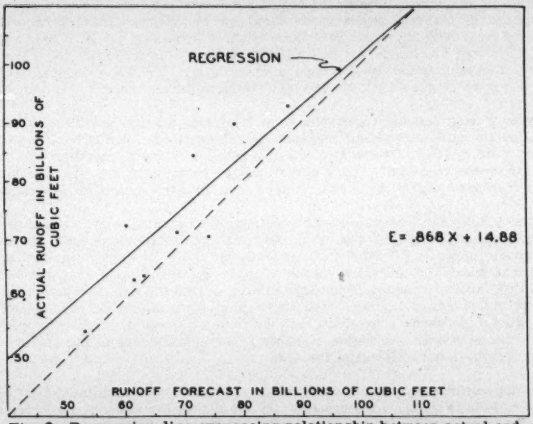

Fig. 2--Regression-line expressing relationship between actual and forecast runoff, in billions of cubic feet, based on snow-survey and precipitation records for the entire period 1926 to 1942

most probable precipitation after the end of March. All figures were expressed in billions of cubic feet (BCF). The results of the first ten years from 1926 to 1935 have been summarized and discussed by HINTON [see 1 of "References" at end of paper].

According to the data presented in HINTON'S paper, the predicted stream-flow has been less than the actual stream-flow in nine years out of ten. This fact led to the thought that subsequent forecasts (1936 to 1942) might have been improved if these ten years of records had been used as a modifying basis for future predictions. To test this hypothesis the following analysis was made.

The actual annual stream-flow for the first ten years, 1926 to 1935, was plotted against the

Table 1--Summary of actual and forecast runoff for period 1936 to 1942

Year	Actual annual runoff	Forecast runoff		Actual error		Standard error of forecast
		Based on snow-survey and precipitation-record	Based on regression	Based on snow-survey and precipitation-record	Based on regression	
	BCF[a]	BCF	BCF	BCF	BCF	BCF
1936	91.8	67.8	73.7	-24.0	-18.1	±2.19
1937	59.9	55.2	62.8	- 4.7	2.9	±2.92
1938	54.9	49.3	57.7	- 5.6	2.8	±3.69
1939	73.2	79.5	83.9	6.3	10.7	±3.16
1940	65.7	51.3	59.4	-14.4	- 6.3	±3.42
1941	73.9	70.0	75.6	- 3.9	1.7	±2.26
1942	79.6	73.0	78.2	- 6.6	- 1.4	±2.46
Total error		.....	.....	65.5	43.9	.....
Mean annual error		.....	.....	9.4	6.3	.....
Improvement by use of regression-values: (9.4 - 6.3) = 3.1 BCF						

[a]BCF = billion cubic feet.

predicted stream-flow based on snow-survey and precipitation-records (Fig. 1). A regression-line was fitted to the plotted points by the method of least squares [2]. The regression-line fell to the left of the "dashed" line representing perfect correlation between predicted and actual stream-flow, indicating that on the average the predicted stream-flow has been less than the actual. This implies that subsequent predictions might have been improved if they had been increased by the amounts represented by the vertical distances between the "dashed" line and the regression-line. For example, if the runoff-forecast based on the snow-survey and precipitation-records for any year was 70 BCF, an improvement might have been attained by adding 5.6 BCF to the prediction, or, in other words, reading the value 75.6 BCF directly from the regression-line. The improved forecast "E" could also be obtained by solving the equation $E = (0.868\ X + 14.88)$, in which 70 BCF is substituted for X, in which case $E = 70(0.868\ X) + 14.88 = 75.6$.

To aid in demonstrating that the regression actually yields a better estimate of runoff than the forecast based solely on snow-survey and precipitation-records, Mr. HINTON kindly furnished the observed data from 1936 to 1942. These data are presented in Table 1, together with the "revised" estimates derived from the regression. The deviations for each year have been summarized and averaged regardless of sign to give the mean annual error for each method of forecasting.

In six out of the seven years the values derived from the regression are closer to the actual runoff than are those based solely on the snow-survey and precipitation-records. In the latter method the mean annual error is 9.4 BCF as compared with 6.3 BCF by the regression. This indicates that an improvement in runoff-forecasting of approximately 33 per cent was obtained by revising the predicted values by means of the regression. From the data available for the regression during 1926-35, the standard error of each regression-forecast can be calculated [2, Sec. 6.19]. These statistics indicate the error with which, in about two times out of three, the predicted runoff should estimate the actual runoff. As shown in Table 1, the actual error of the forecast is smaller than the standard error in four cases out of the seven.

To improve future estimates of runoff a regression-equation was calculated incorporating all the data from 1926 to 1942 (Fig. 2). Although this did not change the slope of the original regression-line appreciably, it is based on more data and should be more reliable in revising future forecasts of runoff. The standard error of each forecast in future years may be calculated from the equation

$$SE_F = \pm \sqrt{(V_{y.x}/17) + (X - \bar{x})^2\ (V_{y.x}/Sx^2)}$$

or, for the equation of 1926-42

$$SE_F = \pm \sqrt{3.4091 + (X - 65.3)^2\ (0.0242)}$$

Thus if, for example, the amount "X" predicted from a snow-survey and precipitation-data in some given year is 70 BCF, the expected amount of runoff should be about $E = 0.818(70) + 18.59 = 75.85$ BCF and the true runoff for the season (with 2:1 odds) should fall within a range of one standard error, or 1.98 BCF; with 19:1 odds it should fall within a range of "t" times the standard error, or $(2.13)(1.98) = \pm 4.22$ BCF on 15 degrees of freedom. Then, in 19 cases out of 20, the

true runoff may be expected to lie between 71.63 and 80.07 BCF.

The correlation-coefficient for the new equation is 0.805 with a corresponding coefficient of determination of 0.649, which indicates that 64.9 per cent of the variation in actual runoff is associated with the variation in snow-survey and precipitation-records upon which the forecast of runoff is based. The 35.1 per cent of the variation in actual runoff unaccounted for may be associated with such factors as variation in ground-water levels from year to year, unpredictable spring rainfall, and insufficient snow-samples which inadequately represent conditions throughout the watershed.

In conclusion, it should be pointed out that the above regression would not be applicable to revise the forecast-runoff if the method of prediction, based on snow-survey and precipitation-records, should be changed radically in the future.

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DISCUSSION

FRED PAGET (Department of Public Works, Sacramento, California)--It appears to me that, although Mr. NIEDERHOF'S suggestions are an improvement over Mr. HINTON'S 1935 methods, they may perhaps lag somewhat behind the present status of generally accepted snow-survey forecasting procedure. The latter's forecasts are based upon runoff of 100 per cent from the winter snow-pack plus runoff of 100 per cent from the precipitation that occurs during the melting period and in nine cases out of ten, as Mr. Niederhof points out, the forecasts have been too low. (The excess may be accounted for by a contribution to runoff from the precipitation during June to September greater than Mr. Hinton assumes.) Mr. Niederhof suggests that Mr. Hinton's forecasts be corrected by a certain amount based upon past performances--the amount to vary with the magnitude of the year.

My thought is that instead of going through these two steps of first forecasting on a premise, which apparently is not correct, and then correcting this inadequate forecast by a varying amount to bring it more in line with what might actually occur, why not do the whole thing in one operation, that is, plot the sum of the snow-pack water-content and the effective precipitation directly against the ensuing runoff according to past performances, and then use this curve directly for forecasting? This suggestion is in accordance with the forecasting methods used by the snow-survey department of the California State Division of Water Resources and has been described in previous Transactions; first in my paper at the Davis meeting in January, 1938, and discussed further in CARL ELGES' paper at the Los Angeles meeting in December, 1938.

SOIL-MOISTURE UNDER A CONIFEROUS FOREST

H. G. Wilm

On the Fraser Experimental Forest, Colorado, a detailed experiment is being conducted to find out the effects of cutting mature lodgepole-pine on various factors affecting water-yield [see 2 and 4 of "References" at end of paper]. Of these factors, soil-moisture deficiencies are particularly graphic in showing the relative consumption of water by uncut and cut-over stands. One year's data have been collected on soil-moisture deficiencies; although the study will require several more years for completion, the methods and results are of sufficient utility to be worth current discussion.

Experimental design--Twenty 5-acre plots in mature lodgepole-pine are being used for this and related experiments. The plots are arranged in four randomized blocks; in each block four plots were cut-over in 1940, leaving one plot uncut and one each with a commercial reserve stand of 0, 2,000, 4,000, or 6,000 board-feet per acre.

The object of this particular experiment is to determine the influence of the cutting treatments on losses of moisture from the soil, including both transpiration and evaporation. The total loss per season on any plot may be expressed by the equation

$$L = (M_1 - M_2) + (P_N - P_P)$$

in which L is the loss, in inches of water, M_1 is the soil-moisture at field-capacity or, as measured in this study, the moisture in the soil just after disappearance of snow in the spring, M_2 is the moisture-content of the soil at the end of the growing season, P_N is the total net rainfall reaching the ground during the subsequent growing season, and P_P is the amount of precipitation which percolates into the soil beyond the greatest sampled depth, at any time between the spring and fall samplings.

For the purposes of this study the total loss, expressed by the above equation, is of less importance than the "net" loss in the autumn--the actual deficiency in soil-moisture below field-capacity, which must be replenished by melting snow before stream-flow can be produced.

Sampling procedures--The following factors must be measured for the soil on each of the 20 plots, within reasonable limits of accuracy: (1) Soil-moisture in spring and autumn; (2) volume-weight; (3) wilting-coefficient; (4) net precipitation reaching the soil during each growing season. Because of the rocky nature of the soil, moisture-contents and volume-weights cannot practically be sampled in a single operation; especially since the volume-weights need be obtained only once and approximately for each plot, while soil-moisture must be sampled with greater precision and twice a year for several years. Thus volume-weights and wilting-coefficients have not yet been obtained, while soil-moisture data by weight are already available for one complete season (1941). Precise data have also been obtained on net precipitation (2).

In sampling for soil-moisture, cores were taken to an 18-inch depth with a two-inch post-hole auger, at ten randomized locations on each of the 20 plots. In these shallow, rocky soils, 18 inches represents the average depth to parent material, and the lower limit of the bulk of lodgepole-pine roots. One set of 200 samples was taken in late September, 1941, and another at the same locations about June 1, 1942. A new set of samples has been taken at newly randomized locations in September, 1942, and will be followed by its own set of spring data and by at least one additional year's observations. All samples were boxed and weighed in the field. In the laboratory, they were oven-dried at 110°C and reweighed. Then each sample was sieved into portions containing material below and above two mm in size, and each portion weighed. In addition, the moisture-equivalent of the fine portion of each sample was obtained by the standard centrifuge-method and, by allowing for the amount of coarse material, was finally expressed on a whole-sample basis.

Analysis--The first year's data for this experiment were analyzed for several purposes: (1) To ascertain preliminary trends in soil-moisture and moisture-losses as affected by timber-cutting; (2) to determine the effectiveness of adjusting the moisture-content of each sample, expressed on a whole-sample basis, to the value which would be expected if all samples contained the same amount of fine material; and (3) to calculate the relation between spring moisture-content, as an estimate of field-capacity, and the moisture-equivalent of each sample. The data on autumn moisture-contents and deficiencies, expressed in grams per 100 grams of oven-dry soil, were analyzed by the covariance method (3), using the "fines" contents of the samples as a concomitant in linear regression. For the relation of field-capacity to moisture-equivalent, a straight line was fitted to the field-data by least squares.

Results--Soil-moisture deficiencies in the season of 1941 were strongly affected by the cutting treatments, with the greatest deficiencies on the uncut plots and the smallest on the clear-cut areas. Autumn soil-moisture contents naturally showed a corresponding trend; this effect, however, became significantly greater than experimental error only after adjustment of all data to the average content of fine material. This adjustment considerably increased the precision of the soil-moisture comparisons; without greatly altering the treatment-variance, it reduced experimental error to one-third of its unadjusted magnitude. The average results by treatments are shown in Table 1, with all data expressed in inches of water in an 18-inch soil-column, on the preliminary assumption of a uniform volume-weight of 1.50 for all plots.

An interesting point is that, while the average "fines" content per plot was highly correlated with autumn soil-moisture ($r = +0.847$), it was not significantly related to moisture-deficiencies ($r = +0.241$). For these soils apparently the autumn deficiency is affected largely by evapotranspirational draft and is relatively independent of variations in soil-texture.

Table 1--Effect of timber-cutting on soil-moisture

Factor	Reserve stand, board-feet per acre				
	(Uncut) 11,890	6,000	4,000	2,000	0
	inch	inch	inch	inch	inch
Autumn soil-moisture[a]	2.67	3.07	3.29	3.12	4.21
Deficiency	1.76	1.53	1.39	1.20	0.32
Net precipitation summer 1941	3.92	4.87	5.19	5.01	5.47
Total loss	5.68	6.40	6.58	6.21	5.79

[a]Adjusted to the average content of fine material.

A high correlation (r = +0.839) was found between spring moisture-contents and moisture-equivalents, both expressed on a whole-sample basis. The relation was expressed by the equation

$$FC = 1.9733(ME) + 0.4408$$

According to this equation, the field-capacities of these soils are approximately two times the moisture-equivalents. This result confirms BROWNING'S data for soils with low moisture-equivalents [1]. Thus the common assumption of equality for field-capacity and moisture-equivalent is apparently false in these soils, and it is believed to be unsound for other coarse-textured soils. At least the assumption should be tested quantitatively in any new study.

On the last line of Table 1 are shown the total moisture-losses under the five treatments, calculated on an approximate basis by adding the total net rainfall for the summer of 1941 to the observed deficiencies. While there seems to be a weak trend among the treatments, it was not significantly greater than chance variations. It may be that most of the autumn deficiency under any one treatment is associated with rainfall-interception rather than with variations in the sum of evaporation and transpiration; high transpiration on uncut plots may be compensated by high evaporation on the cut-over areas.

It should be commented that ordinarily the autumn deficiency rather than total loss must determine the net effect of each treatment on water-yields from snow-melt in the following spring. Since summer rainfall contributes negligible amounts to stream-flow in this zone, its only effect may be to alter the relative autumn deficiency under each treatment. In a very dry or wet season, moisture in the soil under all treatments might be uniformly dry or wet, approaching either the wilting-coefficient or field-capacity.

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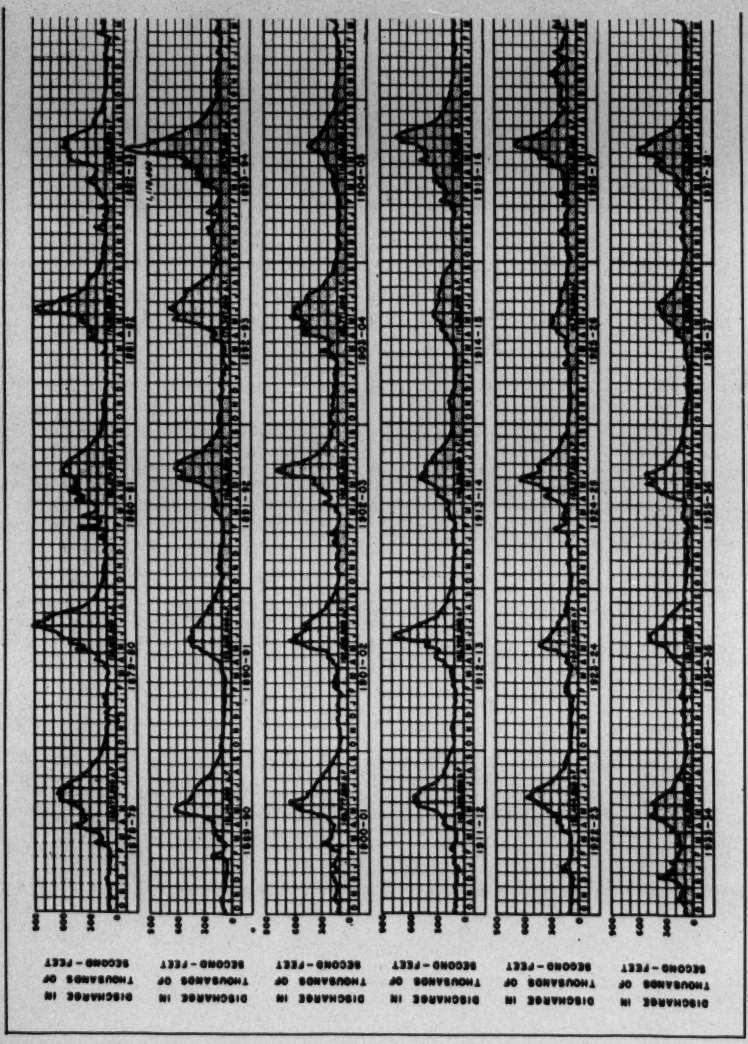
STREAM-FLOW FORECASTING BY PATTERN-BEHAVIOR

Rolla H. Wahle

Purpose and scope--The principle of pattern-repetition as a means for forecasting the annual runoff- and flood-peaks of major rivers was first presented in a brief paper by the author under date of April 9, 1942. Therein was submitted a preliminary application of the pattern-principle to the problem of forecasting the summer peak and total annual runoff of the Columbia River at Cascade Locks, Oregon, for the year 1941-42. Pattern-analysis as presented in our paper of April 1942 introduced an entirely new departure so far as we know in forecasting river-flow. The present paper has been prepared in an effort to amplify the initial preliminary procedure and to extend



Notes: Data furnished by United States Engineer Office, Portland, Oregon, for the 60-year period of 1878 to 1938.
Data for the years 1938 to 1941 furnished by the Bonneville Power Administration.

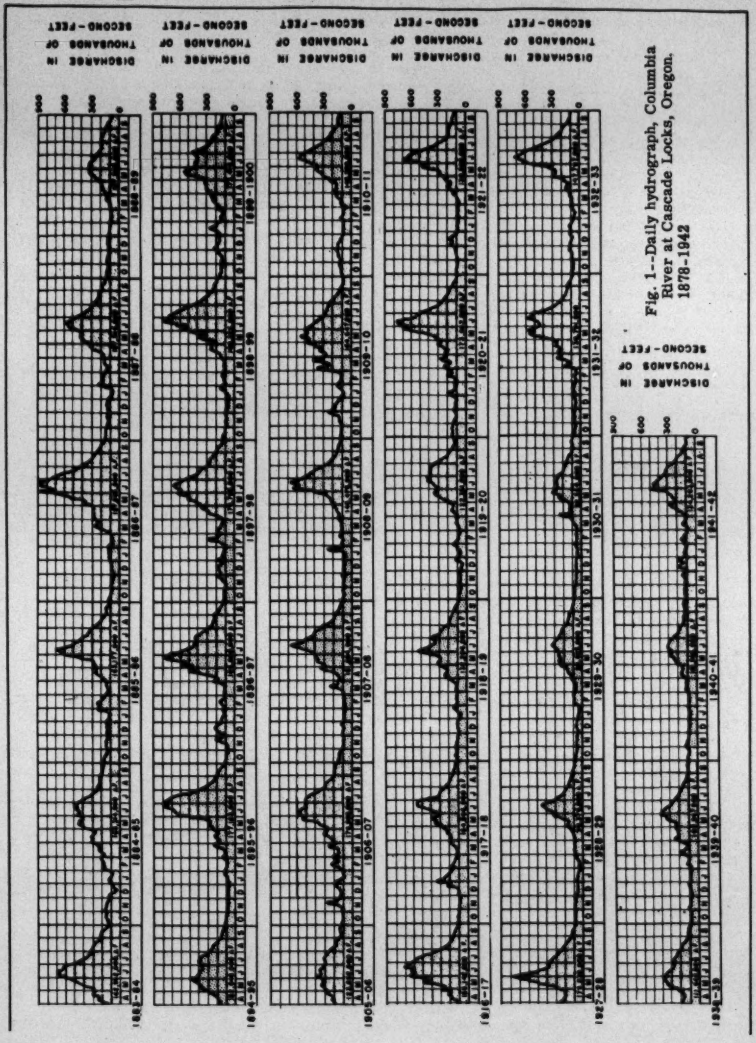


Fig. 1--Daily hydrograph, Columbia River at Cascade Locks, Oregon. 1878-1942

Notes: This hydrograph shows natural stream-flow of the Columbia River at Cascade Locks, Oregon.
Graphs revised October 15, 1942.

original studies by further investigation.

The conclusions reached in regard to the peak- and runoff-totals for the Columbia during 1941-42, as offered in the initial paper, have since been substantiated by actual river-performance. This fact, naturally, has added encouragement to the forecasting principle adopted. These additional studies have greatly increased our personal enthusiasm for the pattern-repetition principle.

Weather-cycles and river-flow--Cyclical activity as a modus operandi is evident throughout nature. This field of study as it relates to weather has enjoyed the extended attention of many students. An extensive study of marine varves made by Halbert Gillett resulted in his definite confirmation of the existence of weather-cycles [H. P. GILLETT, Prospective dry years and their cause, Trans. Amer. Geophys. Union, pp. 1015-1021, 1940]. The same cannot be said for the scholarly investigation of tree-ring records carried forward by Professor Douglass. His studies covering a period of several hundred years were unable to determine any regular rhythm in phenomena of weather. In any event, our personal inquiry has made it evident that whatever cyclical activity may exist as regards the periodic return of wet and dry periods exerts direct bearing upon moisture-accumulation percentages over a series of years rather than with the phenomena of individual years. We therefore have reached the conclusion that, while these studies of the broad swings of weather and climate are of great potential importance, their value at the present time as a means of forecasting stream-flow is extremely limited.

Each individual runoff-year represents a complete cycle in the life of a river. There is an endless periodic alternation between well-defined intervals of low flows and flood-flows. Our problem is therefore basically one of forecasting the magnitude of a known cycle.

The immediate problem--Our immediate problem is to forecast stream-flow characteristics of an ensuing runoff-year.

The water-requirements for irrigation and power-production are of vital and immediate interest. Therefore, any procedure that will obtain a reasonably accurate forecast of the type, magnitude, and total runoff of a major stream during the next six to twelve months is of urgent and vital importance.

Manifestly, stream-flow is the result of a considerable number of interrelated factors. Among these are temperature, precipitation both in the form of rain and snow, ground-retention, conditions of the watershed, and others. These factors are individually diverse and elusive. In addition, they present innumerable possible combinations. These variables explain why flow-forecasts based upon ephemeral data are likely to prove highly unreliable. We have felt impelled, therefore, to eliminate these variables of weather and runoff from direct consideration.

Pattern-repetition implies that phenomena of weather exhibit orderly sequence and in theory, therefore, pattern-analysis indirectly utilizes the final result of those variables in combination at any particular time. On the basis that "like cause produces similar effect" we may well consider that similar flow-conditions in a major river will be followed by conditions closely adhering to the patterns of record.

The theory of pattern-repetition--Rational observation reveals that nature exhibits a powerful tendency to repeat patterns. It is agreed, however, that intervals of repetition may show little or no regularity. In relation to river-flow, observation reveals numerous instances where similar conditions of flow during the first six months of various runoff-years find very similar conditions prevailing during the last six months. The same thing is true of periods covering from three to five years. We do not attempt to explain these phenomena, but offer the statement merely as a demonstrable fact.

Pattern-analysis indicates that when winter and early-spring flows exhibit peculiarities in character, magnitude, and timing, the ensuing six months will adhere closely to the peak-and-magnitude pattern shown by similar previously recorded years.

A daily hydrograph of the Columbia River at Cascade Locks, Oregon, extends back to the year 1878 (see Fig. 1). This is a relatively short period of time for pattern-analysis, but even so, the record definitely proves that similar "first six-month flows" exhibit marked similarity in peaks and runoff-totals that follow. The degree of correlation increases as the first six-month flows attain marked character and magnitude.

The trend of flow--It is interesting to note that the flow of the Columbia River at Cascade Locks, taken in 21-year periods, registers a decline in total flow averaging about 13 per cent per period during the years 1878 to date.

Taken in seven-year periods the decline in flow is very uniform between 1900 and 1941, as shown in Figure 2.

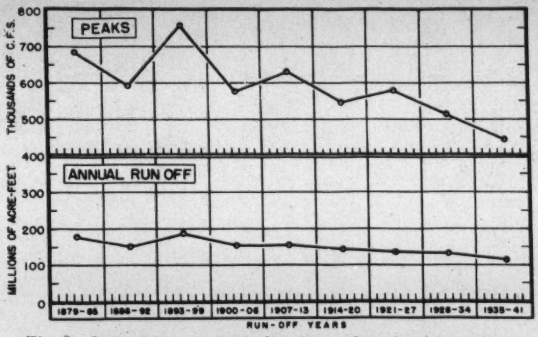


Fig. 2--Seven-year averages of peaks in cfs and total runoff in acre-feet, Columbia River at Cascade Locks, Oregon

Procedure of pattern-selection and analysis--The procedure of pattern-analysis requires certain preliminary selection and tabulation.

First, the hydrographs of the various years of record must be classified in accordance with their first six-month flow. In the case of the Columbia River, the overall classification is as shown by the daily hydrographs of Figure 3 covering the individual runoff-years of 1879 through 1942.

The next step in the procedure of pattern-analysis is to classify all years in groups according to their average flow during the first six months of each runoff-year. Average the peaks and annual runoff-totals of each group and observe the percentage-difference in totals between each such group. This classification is shown by Table 1.

With the tabulations of Table 1 at hand, we may now proceed with the further explanation of the method involved. The application of pattern-analysis, as we conceive it, requires three phases of comparison. These are as follows:

First phase of analysis--The hydrograph of the first six-month flow of the runoff-year under consideration must be compared with the first six-month flow of all previous years. Where one or more examples of close similarity fall in the same classification under Figure 3, these similar years are listed. The total annual runoff and peak together with the average flow for the first six months are tabulated. Averages of tabulated values of annual runoff and peaks constitute the first preliminary forecast.

In those instances where the classification under Figure 3 does not afford a prior close example, then list all past years that most closely simulate the pattern of the first six-month flow under analysis.

Occasionally the average flow for the first six months of the year under analysis will differ materially from the average flow of the selected pattern-years. The difference between the flow-group (Table 1) in which the average of the pattern-years falls, and the average of the group in which the year under analysis falls, is called the "flow-differential." This flow-differential is added to the preliminary forecast (first phase) if the year under analysis falls in a flow-group above that of the pattern-years. The flow-differential is deducted if the year under analysis falls below the flow-group of the pattern-years.

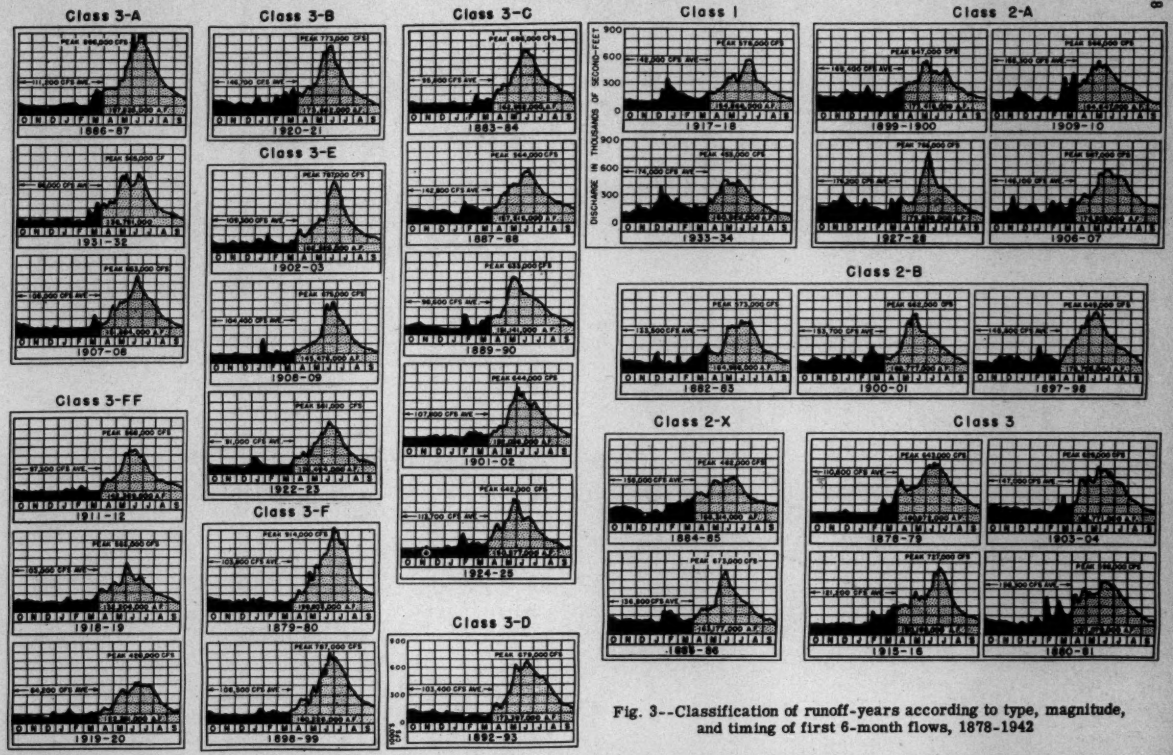


Fig. 3--Classification of runoff-years according to type, magnitude, and timing of first 6-month flows, 1878-1942

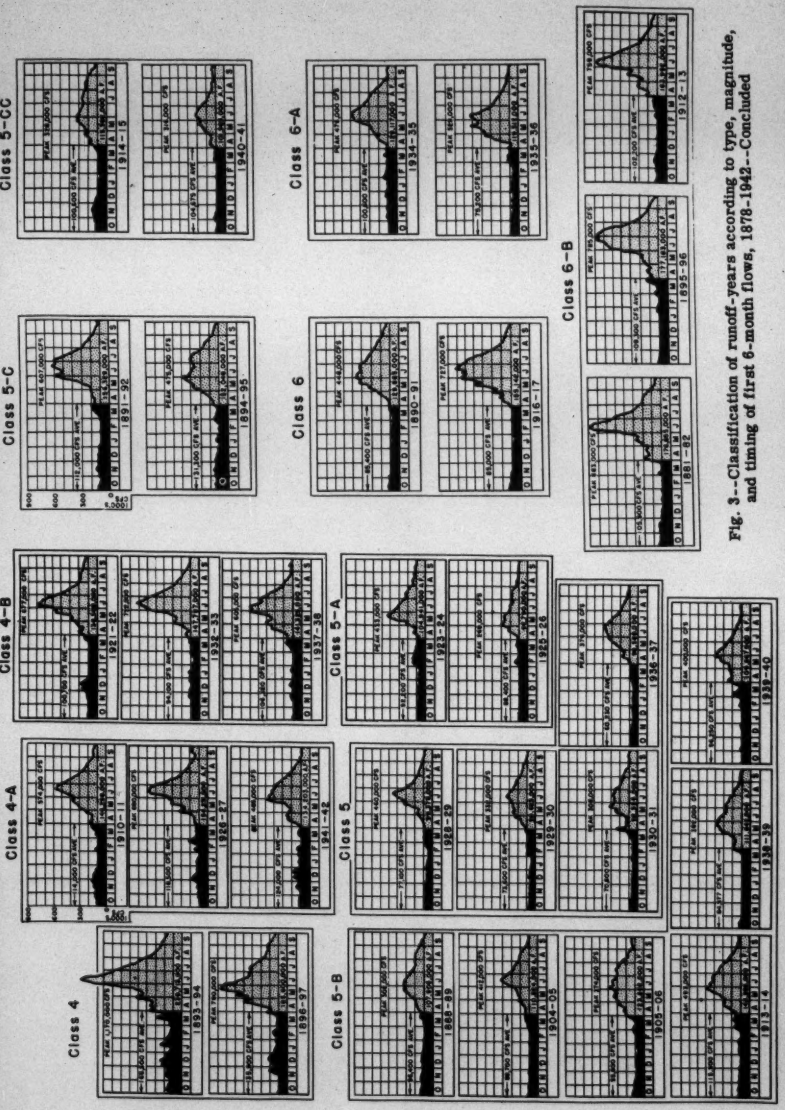


Fig. 3--Classification of runoff-years according to type, magnitude, and timing of first 6-month flows, 1878-1942--Concluded

Table 1--Classification of Columbia River runoff-years at Cascade Locks, Oregon, according to the flow-magnitude of the first six-month period

Flow-group, 1000's of cfs	Runoff-year	Average of first 6-month flows, 1000's cfs	Total annual runoff millions a-f	Peak-flow, 1000's of cfs
60 to 75	1930-31	70.8	92.56	308
	1936-37	60.2	98.59	376
	1929-30	73.6	99.62	332
Average	.....	68.2	97.50	339
75 to 90	1928-29	77.1	99.38	460
	1935-36	75.2	119.51	529
	1916-17	85.0	155.14	727
	1919-20	84.2	122.35	428
	1938-39	85.0	111.64	392
	1890-91	85.4	129.89	448
	1904-05	89.7	110.82	412
	1925-26	88.4	92.79	269
	1931-32	88.0	138.79	565
Average	.....	84.0	120.00	470
90 to 100	1883-84	94.8	169.95	698
	1905-06	93.6	123.66	374
	1922-23	91.0	135.49	581
	1923-24	92.2	104.94	433
	1932-33	94.1	147.79	722
	1888-89	96.4	107.90	302
	1889-90	98.6	151.14	633
	1911-12	97.3	142.37	568
	1939-40	96.2	109.87	400
Average	.....	95.0	132.00	518
100 to 105	1879-80	103.8	199.6	914
	1892-93	103.4	173.4	679
	1907-08	105.0	151.88	653
	1908-09	104.4	145.48	675
	1912-13	102.2	163.99	759
	1914-15	100.6	115.59	328
	1918-19	103.0	132.21	553
	1921-22	100.7	138.51	677
	1934-35	100.6	129.12	476
	1940-41	104.7	101.96	316
Average	.....	102.8	145.21	603
105 to 110	1881-82	105.9	176.85	883
	1895-96	109.3	177.18	785
	1898-99	108.5	180.23	787
	1901-02	107.8	152.04	644
	1902-03	109.3	162.53	787
	1937-38	106.3	141.33	605
Average	.....	107.8	165.00	748
110 to 115	1878-79	110.6	180.97	643
	1886-87	111.2	197.84	896
	1891-92	112.0	156.33	607
	1924-25	113.7	150.58	642
Average	.....	111.8	171.00	697
115 to 125	1913-14	115.9	143.29	493
	1915-16	121.2	180.20	727
	1926-27	118.5	156.23	690
	1941-42	124.0	134.20	485
Average	.....	119.9	153.48	599

Table 1--Classification of Columbia River runoff-years at Cascade Locks, Oregon, according to the flow-magnitude of the first six-month period--Concluded

Flow-group, 1000's of cfs	Runoff-year	Average of first 6-month flows, 1000's cfs	Total annual runoff millions a-f	Peak-flow, 1000's of cfs
125 to 136	1882-83	133.5	164.96	573
	1894-95	131.3	152.05	475
	1896-97	135.9	185.06	780
Average	.....	133.5	167.35	609
136 to 150	1885-86	136.8	163.18	673
	1887-88	142.8	157.52	564
	1897-98	145.6	178.70	649
	1903-04	147.0	185.77	629
	1906-07	146.1	176.50	587
	1917-18	142.0	154.87	578
	1920-21	146.7	173.66	773
Average	.....	143.8	170.00	636
150 to 160	1880-81	158.3	193.07	598
	1884-85	155.0	168.31	482
	1900-01	153.7	168.78	662
	1909-10	155.3	164.65	566
Average	.....	155.5	173.07	577
160 and over	1893-94	165.5	239.71	1,170
	1899-00	169.4	173.42	547
	1927-28	176.2	175.84	766
	1933-34	174.2	160.03	453
Average	.....	171.3	187.25	731
160 and over minus flood-year of 1893-94		173.3	169.76	589

After correction is made for a flow-differential, if such a correction is required, the resulting figures represent the corrected first preliminary forecast of peak-flow and total annual runoff.

Second phase of analysis--The record is now consulted to determine all of the years that closely resemble in pattern of flow the year immediately preceding the one under analysis. This is accomplished by referring to all of those years brought out under the first phase of analysis and then comparing the year that immediately preceded them with the year immediately preceding the year under analysis. All these preceding years should be listed as was done under the first phase. If less than two similar years are found, then the record must be searched for other close approximations. If no further examples exist, then use the one or more already selected. If none has been found, then base the final judgment on the other forecast-phases.

Note the percentage-difference in the average peaks and the average total runoff existing between the first and second years of each pattern-pair. This percentage-difference is then applied to the peak and total in acre-feet of the year immediately before that under analysis. The result is the second preliminary forecast.

Third phase of analysis--The general type of the period under analysis is now examined. For example, the year 1941-42 is preceded by three years of extremely low flows and peaks. We now proceed to determine if any previous similar conditions occurred. In the example afforded by 1941-42, we find three such instances, that is, 1907, 1921, and 1932. Each of these three individual years was preceded by three-year periods exhibiting comparatively low flows and peaks.

The next step is to average the peaks and total flows of each group of three preceding years and determine the relation these totals bear to the pattern-year applying in each instance. For example, the peaks and total-flow figures for the years 1903-04, 1904-05, and 1905-06, are averaged. These averages are then compared with the peak and total-flow figures for the pattern-year of 1906-07. This determines the percentage-difference between the three previous years and the pattern-year. The percentage-difference is then applied to the averages of the peaks and total runoff of the three years immediately preceding 1941-42, the latter being the year under analysis in this example.

This third phase of analysis is extremely important as a forecast-indicator and this is particularly true in those cases where the first six-month flow under analysis lacks distinctive characteristics, or where no close pattern-years are found. A general rule is to give the greatest weight to that forecast-phase exhibiting the most marked similarity to the year and period under consideration.

Examples where emphasis may be placed on the pattern-years individually selected without regard to period-indications are supplied by Classes 1 and 2, Class 5, and Class 6-B, all shown in Figure 3; yet even here many examples show that combination of all phases of analysis provides the most accurate results. Examples where period-classification is most noteworthy are supplied by the years 1920-21, 1934-35, 1941-42, and others.

Examples of pattern-forecasting--For the purpose of clarifying the foregoing procedure, we offer two examples of pattern-analysis.

Example I: Initially let us examine the first six-month flow of the runoff-year of 1912-13. An examination of the hydrographs provides two years closely approximating in character the first six-month flow of 1912-13. These years are as follows:

Runoff-year	First 6-month flow, 1000's of cfs	Total annual runoff, millions of a-f	Peak-flow, 1000's of cfs
1881-82	105.9	177	883
1895-96	109.3	177	785
Average	107.6 (a)	177	834
1912-13	102.2 (b)	....	....

Referring the above first six-month flows, (a) and (b), to Table 1, we find a flow-differential of 19.4 per cent for the peaks and 12 per cent for the annual runoff. Thus the average annual runoffs and peaks, respectively, are for flow-group from 100,000 to 105,000 cfs, 145,210,000 acre-feet and 603,000 cfs, and for flow-group from 105,000 to 110,000 cfs, 165,000,000 acre-feet and 748,000 cfs; the resulting flow-differentials are then -12 and -19.4 per cent. These percentages deducted from the averages given by 1881-82 and 1895-96 show the following: (1.00 - 0.12) (177,000) = 156,000 acre-feet for annual runoff; (1.00 - 0.194) (834,000) = 672,000 cfs for peak.

This constitutes the first preliminary forecast and meets the conditions of the first phase of analysis.

In the second phase of analysis, the following years meet the conditions imposed. It will be noted that only one of the two years brought out in the first phase of analysis can be used here. This is because the year 1880-81 does not compare with 1911-12, the year preceding the one under analysis. We do, however, find that 1895-96 can be used because the preceding year of 1894-95 does compare with 1911-12. This is only one example, however, and we must search the record for at least two more. These are supplied by the years 1890-91 and 1901-02, as they closely approximate the characteristics exhibited by 1911-12 and are followed by flows similar to those during the first six months of 1912-13.

Next, tabulate these years and determine the percentage-variance between the pairs as indicated below.

Runoff-year	Total annual runoff, millions of a-f	Percentage-difference	Peak-flow, 1000's of cfs	Percentage-difference
1890-91	130		448	
1891-92	156	+16.7	607	+26.2
1894-95	152		475	
1895-96	177	+14.2	785	+39.5
1901-02	152		644	
1902-03	163	+ 6.2	787	+18.2
Average difference		+12.4		+28
1911-12	142		568	

The foregoing shows that in the second year of each pair, the annual runoff averaged 12.4 per cent greater than in the first year, and the peaks averaged 28 per cent greater. These differences applied to the year 1911-12, give the following results and supply the second preliminary forecast for the runoff-year 1912-13: (1.00 + 0.124) (142,000,000) = 162,000,000 acre-feet for total annual runoff; (1.00 + 0.28) (568,000) = 788,000 cfs for annual peak.

The third phase of analysis is not applicable to the year 1912-13 because the hydrograph shows no similar period of years such as that immediately preceding 1912-13. We must therefore use the results obtained from the first and second phases of analysis for our forecast. These are as follows:

Forecast	Annual runoff, acre-feet	Peak, cfs
First preliminary	156,000,000	672,000
Second preliminary	162,000,000	788,000
Third preliminary	None	None
Average and final	159,000,000	730,000
Actual from hydrograph	163,992,000	759,000
Difference in per cent	3	4

Example II: For the second example of pattern-analysis let us consider the runoff-year of 1914-15. This year is of particular interest because it was one of the three lowest years of record up to that time and in addition, the preceding years exhibited distinctive character for which two prior examples were available.

Figure 3 shows the year 1914-15 as falling in Class 5-CC. This sub-class afforded no prior examples. Class 5 in its entirety, however, supplies the following close examples:

Runoff-year	First 6-month flow, 1000's of cfs	Total annual runoff, millions of a-f	Peak-flow, 1000's of cfs
1888-89	96.4	108	302
1904-05	89.7	111	412
1905-06	93.6	124	374
Averages	93.2	114	362
1914-15	100.6	....	....

Consulting Table 1 we obtain average annual runoffs and peaks, respectively, for flow-group of 90,000 to 100,000 cfs, 132,000,000 acre-feet and 518,000 cfs, and for flow-group of 100,000 to 105,000 cfs, 145,000,000 acre-feet and 603,000 cfs; the resulting flow-differentials are then +9 and +14.1 per cent. These percentages added to averages given by 1888-89, 1904-05, and 1905-06, give (1.00 + 0.09) (114,000,000) = 125,000,000 acre-feet for annual runoff and (1.00 + 0.141) (362,000) = 421,000 cfs for peak.

This constitutes the first preliminary forecast and meets the conditions of the first phase of analysis.

The second phase of analysis provides the following selection and tabulations:

Runoff-year	Total annual runoff, millions of a-f	Percentage-difference	Peak-flow, 1000's of cfs	Percentage-difference
1887-88	158		564	
1888-89	108	-31.6	302	-35
1903-04	186		629	
1904-05	111	-40.4	412	-34.5
Average difference		-36		-34.7
1913-14	143		493	

The foregoing shows that in the second year of each pair the annual runoff averaged 36 per cent less than the first year, and the peaks averaged 34.7 per cent less. These differences applied to the year 1913-14 give us the following results and supply the second preliminary forecast for the runoff-year of 1914-15: (1.00 - 0.36) (143,000) = 91,000,000 acre-feet for total annual runoff; (1.00 - 0.347) (493,000) = 322,000 cfs for annual peak.

The third phase of analysis brings out the following selection and tabulation:

Runoff-year	Total annual runoff, millions of a-f	Percentage-difference	Peak-flow, 1000's of cfs	Percentage-difference
1886-87	198		896	
1887-88	158		564	
Average	178		730	
1888-89	108	-39.3	302	-58.7
1902-03	163		787	
1903-04	186		629	
Average	174		708	
1904-05	111	-36.4	412	-41.9
Average difference		-37.8		-50.3
1912-13	164		759	
1913-14	143		493	
Average	154		626	

The average differences shown above are now applied to the average of the totals for 1912-13 and 1913-14. This gives us our third preliminary forecast as follows: (1.00 - 0.378) (154,000,000) = 95,800,000 acre-feet for total annual runoff; (1.00 - 0.503) (626,000) = 311,000 cfs for annual peak.

Consideration of the year 1914-15 permitted use of all three phases of the procedure of analysis. The various preliminary totals and the final results are as follows:

Forecast	Annual runoff, acre-feet	Peak, cfs
First preliminary	125,000,000	421,000
Second preliminary	91,000,000	322,000
Third preliminary	96,000,000	311,000
Average and final	104,000,000	351,000
Actual from hydrograph	115,592,000	328,000
Difference in per cent	11	6

Procedure is amply illustrated with the foregoing examples. While the method of analysis given may be considered as the "Basic formula," it is also true that individual characteristics exhibited by different years may be utilized for a closer check on the totals obtained. For example, if we consider the year 1933-34, the record supplies two prior similar occurrences, 1917-18 and, to a less degree, 1885-86.

It will be noted that the peaks and magnitude of flow during the first six months of these years exhibit a definite relationship to the yearly peaks that follow (see Fig. 4).

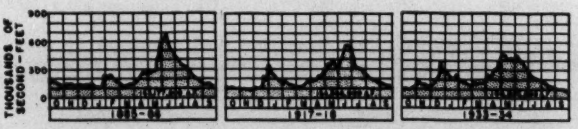


Fig. 4--Comparison of hydrographs for the years 1886, 1918, and 1934

Only occasionally is a pattern found to be subject to this further analysis over and above the "Basic formula." However, when possible, this type of additional consideration should be utilized in arriving at a final conclusion.

We believe the foregoing examples and considerations supply ample illustration of the methods we have utilized. It is of further interest to consider the results achieved by application of these methods over a considerable period of time simply as a means of empirically testing principle involved.

A 30-year test application of pattern-analysis--It is of interest and value to obtain an idea of what may be expected of pattern-analysis in forecasting annual peak-flows and total annual runoff over considerable periods of time. To this end we have prepared two studies which indicate what might be anticipated as to consistency and overall accuracy of results.

The fundamental idea of pattern-analysis is that "similar first six-month flows favor a similar succeeding flow." The basic formula of pattern-analysis represents an extension of this fundamental idea.

Figure 5 shows a complete record of annual peaks and total annual values of runoff for the runoff-years of 1913 through 1942, together with the pattern-analysis test-forecasts covering each runoff-year.

These test-forecasts in Figure 5 are derived from the first phase of the basic-forecast formula; no pattern-classification was applied. The pattern-years for the individual first six-month flows were selected visually from the hydrograph on the basis of conformity, according to type, magnitude, and general similarity of flow. In many instances no previous close patterns were found and in these instances the nearest first six-month flow-types were used as pattern-years. The average peaks and total runoff of these years, plus or minus a preliminary flow-differential percentage when applicable, represented the extent of the test-forecasts of Figure 5.

The preliminary flow-differential percentages used in preparing the test-forecasts of Figure 5 were obtained by simply classifying the first six-month flow of all preceding years into arbitrary groups of 10,000 second-feet of flow-variation. No attempt was made to arrive at the more representative group-classification of flow-magnitudes employed by the basic formula.

Figure 6 likewise shows a complete record of the peaks and total annual runoff characterizing the runoff-years 1913 through 1942. In the case of the test-forecasts of Figure 6, however, the complete basic formula has been employed in the manner shown in examples contained in this study.

In preparing the test-forecasts given in both Figures 5 and 6, all portions of the hydrograph ahead of the six-month period under analysis were completely covered in order to eliminate, as far as possible, any influence of visual bias.

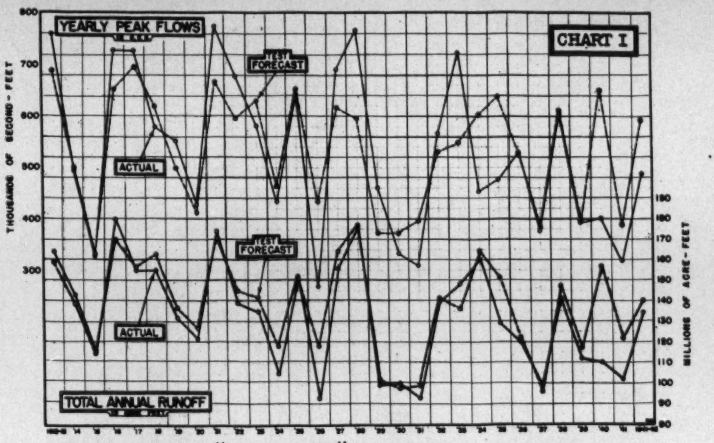


Fig. 5--Pattern-analysis "test-forecasts," Columbia River at Cascade Locks, Oregon
(Based solely on unclassified yearly pattern-similarity of first 6-month flows)

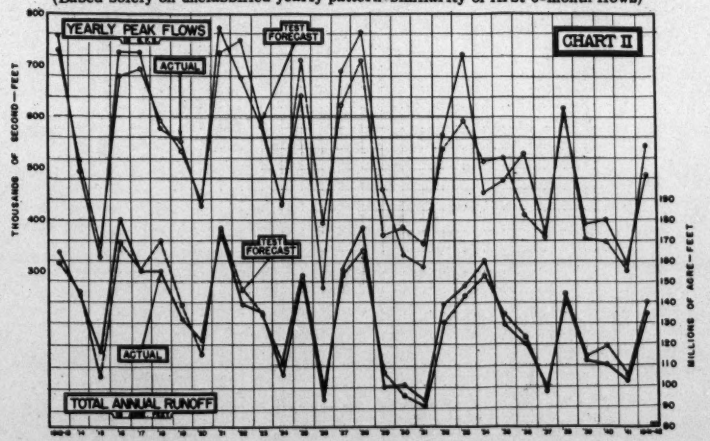


Fig. 6--Pattern-analysis "test-forecasts," Columbia River at Cascade Locks, Oregon
[(Derived from classified first 6-month flow of pattern-years plus period-patterns (basic formula)]

In Figure 5, the correlation between test-forecasts and the actual succeeding occurrences were extremely gratifying in that they indicated that even the most elementary application of pattern-analysis is capable of an accuracy and consistency far beyond the limits of pure coincidence.

The test-forecasts given by Figure 6 were evolved through complete application of the basic formula, or full three-phase analysis plus cross-checking by means of outstanding peculiarities of pattern. Comparison of results shown by these Figures reveals a definite improvement in overall accuracy when the complete basic formula is employed wherever possible. This improvement is well indicated by the following summary:

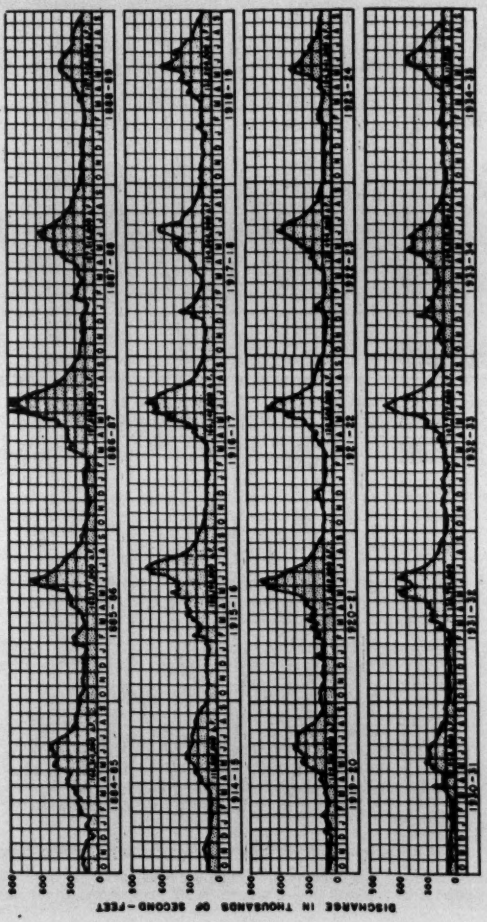
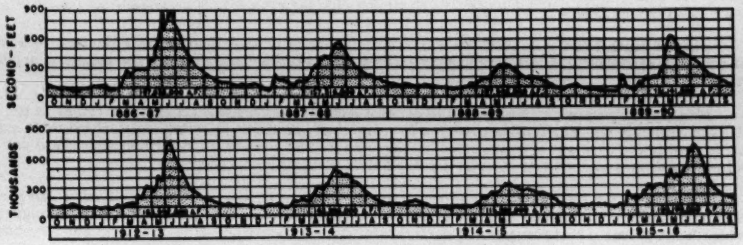


Fig. 7--Four-year "period-patterns"

Item	Figure 5	Figure 6
Average per cent deviation of test-forecast from actual runoff	5.83	4.06
Average per cent deviation of test-forecast from actual peaks	12.53	8.07
Average increase in accuracy of test-forecasts (Figure 6 over Figure 5) for runoff	30.4	
Average increase in accuracy of test-forecasts (Figure 6 over Figure 5) for peaks	35.6	
Per cent of total forecasts falling within 10 per cent limits for runoff	86.6	100.00
Per cent of total forecasts falling within 15 per cent limits for peaks	66.6	86.6

Period-patterns: Additional possibilities--It is of interest to note that application of phase three of the basic formula suggests a possible worthwhile extension of the principle of pattern-analysis and forecasting. This extension involves the intriguing possibility of being able to reasonably gage the general character and extent of flows and peaks for an entire year in advance for all those cases where distinctive pattern characterizes a period.

Several examples of period-patterns are presented in Figures 7 and 8 showing hydrographs of the Columbia River at Cascade Locks, Oregon.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300
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O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S
1913-13
1913-14
1914-15
1915-16

Fig. 8--Three-year "period-patterns"

The foregoing period-comparisons definitely imply "ordered design" in phenomena of weather as opposed to caprice and chance. Application of the principle of pattern-repetition to such distinctive periods offers the probability of a gratifying degree of accuracy in forecasting the type and nature of forthcoming river-flows a full year in advance. The value of this type of forecast would accrue principally to power-production, just as would forecasts of the critical first six-month flow of a runoff-year.

Conclusion

We must, to a large extent, permit the theory of pattern-behavior and our analysis thereof to speak for itself. The evidence herewith presented lends definite weight to the validity of this type of approach as a means for forecasting river-flows. We conceive the situation as one largely applying to major rivers where extensive watersheds rule out the vagaries of caprice of weather in isolated sections. Small watersheds might be found to apply, but this seems problematical.

Pattern-behavior as an indicator of coming river-flow is particularly of interest as regards extremes--extreme low flow-years and years of flood. A foreknowledge of the imminence of these extreme conditions can well be of major value. Any method of forecasting that permits an enlargement of prior knowledge of low runoff-years permits extreme conservation of water-resources for power, irrigation, and navigation. Maximum anticipation on the other hand permits orderly preparation for flood-crests to the end that all interests will realize the most good and suffer the least harm.

It is hoped that others will be sufficiently impressed with this theory of pattern-repetition that they will also apply the principles we have outlined to other great watersheds.

Bonneville Administration,
Portland, Oregon

DISCUSSION

BERTRAM S. BARNES (Regional Engineer, United States Weather Bureau, San Francisco, California)--Does the author consider his method satisfactory on streams that are principally rain-fed, such as the Ohio? Has it been tried where snow is not a large factor? Would he consider that the success of the method is on account of the presence of snow? Is the pattern of the first six months dictated by the nature and extent of the snow in the same way as the runoff for the second six months? (See p. 96 for reply by the author to these queries.)

THE USE OF SNOW-SURVEYS AS AN AID IN FLOOD-CONTROL OPERATION OF RESERVOIRS

Fred Paget

On the Sierran tributaries of the San Joaquin River, floods are of two types: (1) Winter floods from heavy rains and (2) late-spring floods from melting snow.

In this area heavy rains which may occur at any time from the first of November to the end of April may cause floods while melting snows may cause floods from the first of May until the end of July. The rain-floods can be predicted only a few days in advance at the most, but by means of snow-surveys the floods from melting snows can be foretold many weeks before they occur.

For the control of floods from the Sierras, investigations have been made in the past by several different organizations to determine the degree of protection desirable and the means of providing it.

It is not the purpose of this report to present another such study. Its purpose rather is to draw attention to the information revealed by snow-surveys and to show how this information may be applied to the problem of operation of reservoirs for the control of snow-melt floods and yet allow maximum conservation of water for irrigation and power-purposes.

A review of the statistical data gathered during the past 12 years during which snow-surveys have been made in California reveals a close correlation between snowpack and ensuing runoff which holds promise that forecasts of such floods within an accuracy of ten per cent can be made on many of the streams of the San Joaquin Valley.

With forecasts of this accuracy, snow-surveys make it possible to operate a reservoir for protection from snow-melt floods and yet have it full at the end of the flood-runoff season.

The following study presents the correlation between snow-survey measurements and runoff on the Kings River, and using this stream as an example shows how advance information as to snow-melt runoff may be applied to the dual problem of flood-control and water-conservation in operation of the proposed Pine Flat Dam on the Kings River.

During the course of this study other streams also were investigated and the method described herein was found to apply equally well to all. For the sake of brevity, the discussion herein is limited to the Kings River.

Snow-survey data

Runoff-forecasts from snow-survey of April 1--The water-content of the snowpack in each watershed is determined by taking a mean of measurements at many places strategically located in the watershed.

The main survey is made during the closing days of March and the early days of April. At this time usually the winter's snowpack is all down and the snow-melt runoff is about to start, and from the snow-surveys a reasonably accurate forecast can be made of the total amount of water to be expected during the snow-melt period April 1 to July 31. This forecast assumes normal precipitation on the watershed during April. A correction is made about May 1 if the precipitation in April departs from normal.

Figure 1 shows for the Kings River the presently established relationship between the total discharge at Piedra during the snow-melt period and the water-content of the snowpack in the watershed as measured at the first of April.

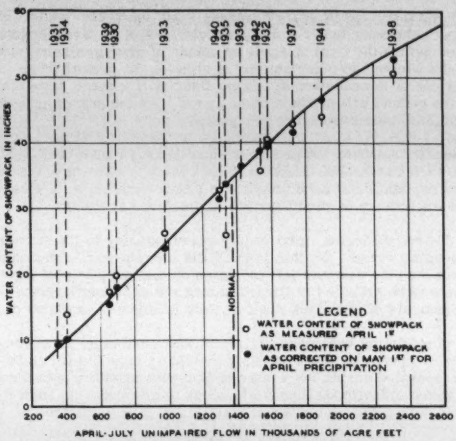


Fig. 1--Relation of snowpack water-content to unimpaired flow of river. Kings River at Piedra

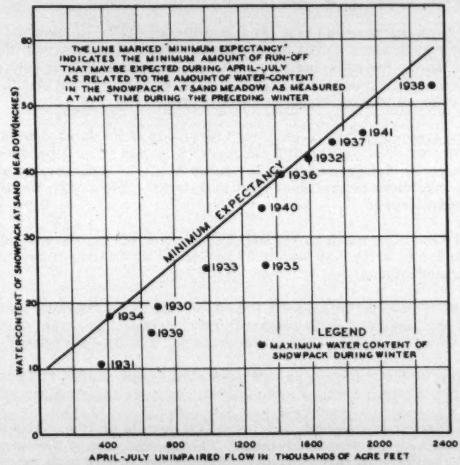

THE LINE MARKED "MINIMUM EXPECTANCY" INDICATES THE MINIMUM AMOUNT OF RUN-OFF THAT MAY BE EXPECTED DURING APRIL-JULY AS RELATED TO THE AMOUNT OF WATER-CONTENT IN THE SNOWPACK AT SAND MEADOW AS MEASURED AT ANY TIME DURING THE PRECEDING WINTER
MINIMUM EXPECTANCY
1938
1941
1937
1932
1936
1940
1933
1935
1930
1934
1939
1931
LEGEND
MAXIMUM WATER CONTENT OF SNOWPACK DURING WINTER
WATER-CONTENT OF SNOWPACK AT SAND MEADOW (INCHES)
APRIL-JULY UNIMPAIRED FLOW IN THOUSANDS OF ACRE FEET

Fig. 2--Runoff-expectancy as indicated by snow-surveys at Sand Meadow, Kings River at Piedra

Inspection of this Figure reveals that during the period of record, forecasts made from this curve early in April would during wet years have had an accuracy within 10 per cent. Forecasts made after the first of May of those years would have had an accuracy within four per cent.

Forecasts in the past have not always been as accurate as the present curve would indicate, but each year yields more data upon which to base forecasting procedure and accuracy continues to improve.

Runoff-expectations indicated by early progress snow-surveys--While final forecasts of runoff cannot be made until the snow is all down, yet some idea of the expectations for snow-melt runoff can be obtained before the first of April by means of progress snow-surveys made from time to time during the winter. For any amount of snow on the ground there is a certain minimum amount of runoff that can be depended upon. Regardless of how much snow may fall later on, any quantity of snow on the ground will produce some runoff. As the season progresses and more is added to the pack, the minimum expectancy increases.

Because of inadequate finances the progress snow-surveys have been limited to one or two key snow-courses in each watershed. Lacking more complete coverage, the records of the progress snow-surveys for the key station at Sand Meadow in Kings Watershed have been used to compile Figure 2 showing the expectancy of runoff for the Kings River at Piedra.

Figure 2 shows the runoff during April to July corresponding to the maximum snowpack measured during the preceding winter. On this Figure, the line marked "minimum expectancy" drawn through the points to the extreme left indicates on the basis of past experience the minimum amount of runoff that may be expected at Piedra during the snow-melt period of April to July corresponding to measurements of snowpack made at Sand Meadow at any time during the winter.

This knowledge of minimum expectancy of runoff as revealed by progress snow-surveys can not be used in the winter operation of a reservoir primarily intended for flood-control, since such a reservoir would be operated during the winter in accordance with a prearranged plan devised to provide protection against rain-floods that might occur at any time. In such a case the snow on the ground at any time during the winter would make little, if any, difference.

However, in the operation of a reservoir primarily devoted to water-conservation the progress snow-surveys will on wet years allow maintenance of some measure of protection against rain-floods longer than would otherwise be done.

When progress snow-surveys indicate the minimum supply from snow will be large enough to satisfy anticipated demands and also fill the reservoir, there would be from then on no object in filling the reservoir before the snow-melt starts. Instead, space may be kept empty to provide a measure of protection against possible late rain-floods, with assurance that the space so kept empty can be filled later on, during the snow-melt season.

Influence of temperature on runoff--Although forecasts of the total amount of runoff can be made, the actual distribution of the runoff from month to month is so dependent upon temperatures that it cannot accurately be determined very far ahead of time. However, by platting a superimposed graph of daily maximum temperatures and daily river-discharges, the trend of the runoff can be foreseen to some degree.

No temperature-recording stations are maintained up in the snow-covered area, but reports on temperature from towns in the San Joaquin Valley serve as a fairly satisfactory index to increasing mountain temperatures.

On Figure 3 is shown for the snow-melt season of 1938 the mean daily flow of the Kings River at Piedra along with the maximum daily temperature at Fresno. For want of a better name, this coupled curve will in this discussion be referred to as a "thermo-hydrograph"

Very little melting of the snowpack is indicated until temperatures at Fresno reach 80° F. Above that the rate of melting increases as temperatures rise and decreases as temperatures drop.

Examining this thermo-hydrograph, it is seen that despite daily variations the trend of the temperatures is upwards as the season advances. This is also true of the runoff until the time when the snowpack is so depleted that increased temperature cannot melt more snow each day. After this maximum point the general trend of the runoff is downward.

The time at which the runoff changes from an upward trend to a downward trend is somewhat difficult to determine readily on the thermo-hydrograph platted from the daily data because of the many minor variations. To overcome this difficulty ten-day running means have been worked up for both the daily temperatures and the daily runoff. These are platted on the "ten-day mean" thermo-hydrograph on Figure 4. The flattening of the daily variations makes it much easier to determine the period during which the trend of the runoff begins to decline.

In the operation of reservoirs these thermo-hydrographs should be very helpful. Not only

could the daily peaks be foreseen to a certain extent several days in advance, but also the start of the decline in runoff could be recognized in ample time to insure that water needed for storage be not wasted needlessly.

Proposed Pine Flat Dam

The physical characteristics of the proposed Pine Flat Dam on the Kings River are set forth in House Document No. 631, as presented to the Third Session of the 76th Congress by the U. S. Bureau of Reclamation on February 12, 1940. The proposed reservoir with a capacity of 1,000,000 acre-feet will have demands upon it in accordance with the data listed in Table 1. (All data abstracted from House Document No. 631.) Demands of irrigation will be as listed in columns

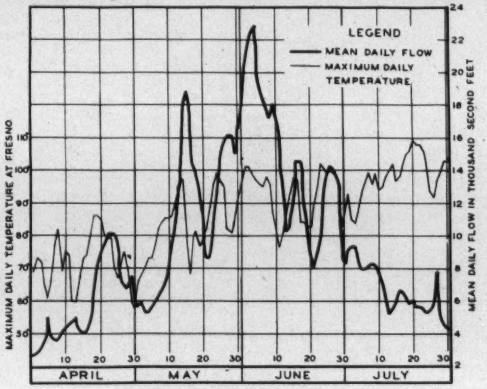


Fig. 3--Thermo-hydrograph, daily for 1938, Kings River at Piedra

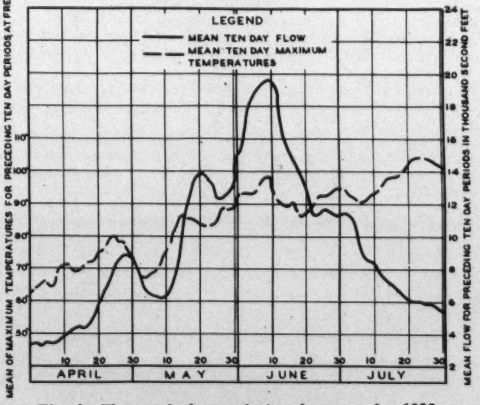

LEGEND
MEAN TEN DAY FLOW
MEAN TEN DAY MAXIMUM TEMPERATURES
MEAN OF MAXIMUM TEMPERATURES FOR PRECEDING TEN DAY PERIODS AT FRESNO
MEAN FLOW FOR PRECEDING TEN DAY PERIODS IN THOUSAND SECOND FEET
APRIL
MAY
JUNE
JULY

Fig. 4--Thermo-hydrograph, ten-day mean for 1938, Kings River at Piedra

(2) and (3). Power-demand with one of the three units operating (initial development) will be as shown in columns (4) and (5). Maximum allowable discharges will be as listed in columns (7) and (8).

In the following discussion the figures for the flow of the Kings River are as measured at the Piedra Gaging-Station which is situated a few miles below the site of the proposed Pine Flat Dam.

Table 1

Month	Irrigation-demands		Power-demands		Normal flow of Kings River	Maximum allowable releases Fresno Slough Cap 6,000 second-feet	
						Ground-water low	Ground-water high
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	a-f	s-f	a-f	s-f	a-f		
Jan.	15,000	240	96,000	1,567	71,000	7,000	6,200
Feb.	46,000	830	87,000	1,567	84,000	7,800	6,800
Mar.	107,000	1,740	96,000	1,567	133,000	9,700	7,800
Apr.	183,000	3,080	93,000	1,567	239,000	12,200	9,000
May	244,000	3,970	96,000	1,567	478,000	16,600	10,000
June	259,000	4,350	93,000	1,567	464,000	17,200	10,200
July	259,000	4,210	96,000	1,567	194,000	16,200	10,200
Aug.	214,000	3,480	96,000	1,567	57,000	.....	.....
Sep.	122,000	2,050	93,000	1,567	23,000	.....	.....
Oct.	61,000	990	96,000	1,567	25,000	.....	.....
Nov.	15,000	250	93,000	1,567	26,000	6,800	6,200
Dec.	0,000	0	96,000	1,567	36,000	6,000	6,200
	1,525,000	.....	1,131,000	.....	1,830,000	.....	.....

Note: Minimum amount of water in storage required for full power head 120,000 acre-feet.

Outline of operational procedure--Operation of Pine Flat Reservoir during the winter would depend upon the policy adopted for the control of rain-floods which is not a part of this study.

However, under any policy of operation adopted, prior to April 10, when and if the progress snow-surveys indicate that the expectation of runoff during April to July (see Fig. 2) is greater than the total amount required to simultaneously fill the reservoir and supply current demands of irrigation, releases are increased to provide additional empty storage-space.

After April 10, when forecasts of complete runoff become available (see Fig. 1) the operation of the reservoir would be modified as necessary to control it.

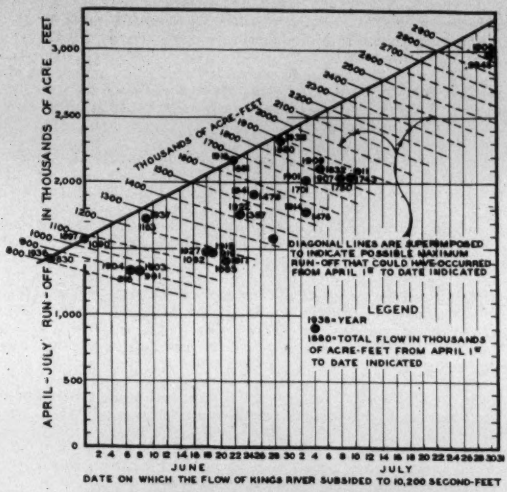
Actual runoff may depart 10 per cent from the forecast, and the manner of its occurrence is subject to wide variations depending upon unpredictable conditions of weather and other factors such as the amount of snow on the watershed, the extent of coverage, and the density of the snow at the end of the winter.

In this study the most unfavorable distribution of occurrence of runoff as disclosed from past records has been used.

Flood-control requires that reservoir-space be provided to take care of early melting, while water-conservation requires that the reservoir be not kept so low that a runoff long drawn out would fail to fill it.

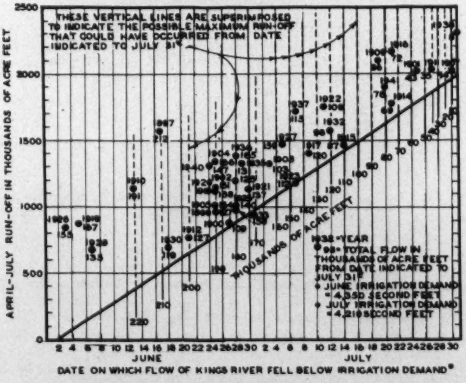
Each year when predetermining an operational schedule, two possible extreme variations in the manner of the occurrence of runoff must be considered. One of these conditions makes flood-control the most difficult and the other makes the filling of the reservoir at the end of the season the most difficult.

Flood-control considerations--Figure 5, compiled from past records, indicates the most dis-


APRIL-JULY RUN-OFF IN THOUSANDS OF ACRE FEET
THOUSANDS OF ACRE-FEET
DIAGONAL LINES ARE SUPERIMPOSED TO INDICATE POSSIBLE MAXIMUM RUN-OFF THAT COULD HAVE OCCURRED FROM APRIL 1ST TO DATE INDICATED
LEGEND
1938=YEAR
1880=TOTAL FLOW IN THOUSANDS OF ACRE-FEET FROM APRIL 1ST TO DATE INDICATED
JUNE
JULY
DATE ON WHICH THE FLOW OF KINGS RIVER SUBSIDED TO 10,200 SECOND-FEET

THE INTERSECTION OF THE APRIL-JULY FORECAST WITH THE HEAVY DIAGONAL LINE INDICATES ON THE ABSCISSA SCALE THE EARLIEST DATE AFTER WHICH THE FLOW OF THE RIVER SHOULD NOT EXCEED 10,200 SECOND FEET, AND INDICATES ON THE SUPERIMPOSED DIAGONAL SCALE THE MAXIMUM TOTAL AMOUNT OF RUN-OFF THAT MIGHT OCCUR FROM APRIL 1ST TO THAT DATE. THIS INDICATES THE MOST UNFAVORABLE DISTRIBUTION OF EARLY RUN-OFF FROM THE STANDPOINT OF FLOOD CONTROL.

Fig. 5--Runoff-distribution graph, early snow-melt runoff, Kings River at Piedra


THESE VERTICAL LINES ARE SUPERIMPOSED TO INDICATE THE POSSIBLE MAXIMUM RUN-OFF THAT COULD HAVE OCCURRED FROM DATE INDICATED TO JULY 31ST
APRIL-JULY RUN-OFF IN THOUSANDS OF ACRE FEET
THOUSANDS OF ACRE-FEET
1938=YEAR
88=TOTAL FLOW IN THOUSANDS OF ACRE FEET FROM DATE INDICATED TO JULY 31ST
JUNE (IRRIGATION DEMAND =4,850 SECOND FEET
JULY IRRIGATION DEMAND =4,210 SECOND FEET
JUNE
JULY
DATE ON WHICH FLOW OF KINGS RIVER FELL BELOW IRRIGATION DEMAND*

THE INTERSECTION OF THE APRIL-JULY FORECAST WITH THE HEAVY DIAGONAL LINE INDICATES ON THE ABSCISSA SCALE THE LATEST DATE AFTER WHICH THE FLOW OF THE RIVER SHOULD NOT EXCEED THE IRRIGATION DEMAND AND INDICATES ON THE SUPERIMPOSED VERTICAL SCALE THE MAXIMUM TOTAL AMOUNT OF RUN-OFF THAT MIGHT OCCUR FROM THAT DATE TO JULY 31ST. THIS INDICATES THE MOST UNFAVORABLE DISTRIBUTION OF RUN-OFF FROM THE STANDPOINT OF FILLING THE RESERVOIR AT THE END OF THE SEASON.

Fig. 6--Runoff-distribution graph, late snow-melt runoff, Kings River at Piedra

advantageous distribution of runoff as affecting flood-control that is apt to occur. Combining both the pre-flood or preparation-period with the flood- or control-period, the Figure shows the earliest date each year that flood-flows from snow have ceased on the Kings River, and indicates to what extent the bulk of the runoff might be concentrated in the early part of the snow-melt season. This is the most critical flood-situation as it restricts to a minimum the time for preparation and control. The Figure also indicates the maximum amount of runoff that might have to be taken care of from April 1 to the end of the flood-period.

Thus anticipating a runoff during April to July of 2,000,000 acre-feet, Figure 5 would indicate that in the case of a very early season all flood-flows might be over and done with on June 16 and that between April 1 and June 16 the total runoff might amount to 1,500,000 acre-feet.

Measures adequate to provide protection against the extreme condition of early runoff as indicated by Figure 5 would be more than adequate should the season be delayed and the bulk of the runoff not occur until later.

Water-conservation considerations--While flood-protection requires that the reservoir not fill until after the river-flows have subsided below the maximum allowable releases, water-conservation requires that the reservoir be full at the end of the snow-melt season. Ordinarily there will be little difficulty in filling the reservoir after flood-danger is over and before the snow-melt finishes.

However, there is the possibility of not filling, if too much space for flood-control is reserved so long that the runoff remaining is not enough to fill the reservoir.

The longer it takes for the flood-runoff to be completed, the earlier the filling of the reservoir must be commenced on account of the greater amount of the total remaining inflow required for current demands and the reduced amount available for storage.

Figure 6, compiled from past records, indicates the latest date each year that flows on the Kings River have exceeded the hypothetical demand of irrigation. For any amount of runoff-forecast, this Figure indicates the extreme length of time during which snow-melt in excess of demands might be expected to occur. The Figure also reveals the maximum amount of runoff which might occur from that date to July 31, thus indicating the balance of the runoff which would occur before the date the flow fell below the irrigation-demand.

Thus anticipating a runoff during April to July of 1,500,000 acre-feet, Figure 6 would indicate that in the case of a very late season flows in excess of the demands of irrigation of 4210 second-feet might occur until July 16 and that from July 16 to July 31 the total runoff might amount to 100,000 acre-feet, and conversely that the flow from April 1 to July 16 might amount to 1,400,000 acre-feet.

If the operation of the reservoir is adjusted to insure filling, should this condition of maximum delayed runoff occur, filling is also assured under all conditions of earlier completion of the run-off.

Operational criteria--The criteria of operation for the control of snow-melt floods on each stream would be different. Those which suggest themselves for Pine Flat Reservoir are:

(1) Prior to April 10, as soon as progress snow-surveys at Sand Meadow indicate a minimum expectancy of runoff during April to July more than sufficient to fill the reservoir and supply the demands during April to July, releases should be increased to provide additional empty storage-space.

(2) After April 10, when complete snow-survey forecasts become available, the criteria are:

(a) To assure of filling, assume that the forecast may be ten per cent high with runoff continuing until late in the season (as indicated by Fig. 6). During the time that the outcome of the runoff is in doubt do not allow the reservoir to empty beyond a point that it would be impossible to fill it under such a delayed distribution of runoff.

(b) To safeguard against flood assume that the forecast may be ten per cent low with heavy early runoff (as indicated by Fig. 5). During the time that the outcome of the runoff is in doubt do not allow the reservoir to fill beyond a point which would result in its overflowing during the flood-period should such conditions of early runoff eventuate.

(c) Follow this intermediate course, protecting against possible flood and assuring of filling, as long as possible. When the point is reached beyond which both conditions cannot be satisfied, the thermo-hydrograph (Figs. 3 and 4) should indicate whether the runoff is going to be less or

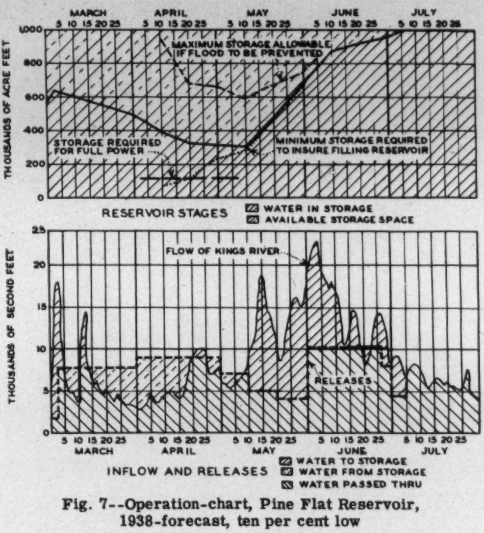


Fig. 7--Operation-chart, Pine Flat Reservoir, 1938-forecast, ten per cent low

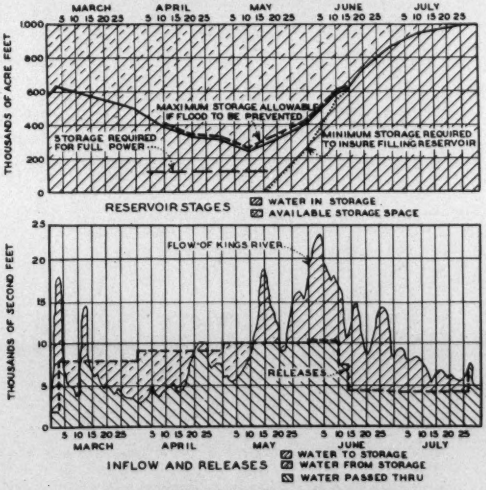


Fig. 8--Operation-chart, Pine Flat Reservoir, 1938-forecast, ten per cent high

greater than the forecast, and the operation during the last part of the season can be properly adjusted to the existing situation.

Application of operational criteria--The system outlined above has been worked out in detail covering the year 1938 for which snow-records are available. During the entire record of the Kings River the flow during the snow-melt period of 1938 was exceeded only in 1906 for which no snow-records are available.

In the hypothetical operation of Pine Flat Reservoir during 1938, as outlined hereafter, it has been assumed that the ground-water table of the agricultural lands was high, having been brought up by the preceding wet year of 1937. The allowable releases are thus limited to those shown in column (8) of Table 1.

Hypothetical operation is shown covering two different situations. In the first example the forecast is assumed ten per cent low; in the second example the forecast is assumed ten per cent too high.

The stage of the reservoir during the winter would be dependent upon the program of operation adopted for the control of winter rain-floods. In this study, in order to supply a starting point the water in storage in Pine Flat Reservoir on March 1, 1938, is arbitrarily assumed as being 568,000 acre-feet.

Operational charts for 1938 are given on Figures 7 and 8. That on Figure 7 shows how the reservoir would have been operated under the foregoing criteria had the forecast been ten per cent low. That on Figure 8 shows the operation had the forecast been ten per cent high. In neither case is hindsight used.

Division of Water Resources,
California Department of Public Works,
Sacramento, California

DISCUSSION

JAMES E. JONES (Department of Water and Power of the City of Los Angeles, California)--The author of this report has presented a correlation between snow-survey data and the runoff of the Kings River in California. The example used shows how the advance information as to snow-melt runoff may be applied to the dual problem of flood-control and water-conservation in the operation of reservoirs in a water-system supplied from natural runoff.

Figure 1 is a starting point fairly familiar to all using snow-survey data for purposes of forecasting stream-runoff.

Figure 2 presents a view that may be required when the season in question is one of subnormal temperatures, or has been preceded by years that would cause great losses from the water-content of the snow-field by reason of the heavy recharge to the underground water. This expectancy must be, to a large degree, based upon a knowledge of the basin held by the forecaster as a matter of historical experience.

Agreement with the statement "Although forecasts of the total amount of runoff can be made, the actual distribution of the runoff from month to month is so dependent upon temperatures that it cannot accurately be determined very far ahead of time" is made as a matter of experience.

The use of the maximum daily temperature at Fresno to plot the "thermo-hydrograph (Figs. 3 and 4) is believed capable of refinement by the use of the daily mean, due to the melting of the snow-field being more probably a result of the effect of both maxima and minima.

The Department of Water and Power of the City of Los Angeles has followed the practice for two years of plotting the mean temperature at Long Valley against the flow of the Owens River and has found that nearly a week's advance notice has been obtained of changes in stream-flow.

Experience has shown that the range between the maxima and minima temperatures at Long Valley is not uniform, having many wide and narrow belts. The melting of the snow-field is believed to more closely follow the mean temperature than either of the two extremes.

The demands upon a reservoir may be of several characters, but the treatment under a mass-curve can be set out according to the special conditions. The plan is usually set by May 1 of each year, but the progress-surveys will have determined to a large measure the season's operations.

Figures 5 and 6 give the approximate early and late dates of snow-melt runoff. These graphs are new to the writer and their construction was not clear from the report as submitted.

Under date of July 2, 1943, FRED PAGET, in reply to a request for data as to the construction of Figures 5 and 6, made the following statements:

> "The heavy diagonal line of Figure 5 determines for any amount of forecast the earliest date by which time the flow from the watershed might fall for keeps to a stage that the outlet channels could safely carry, and also indicates the maximum total amount of water that under such conditions would have to be taken care of up to that date. The heavy diagonal line of Figure 6 determines for any amount forecast the last date upon which the stream-flow might be expected to be greater than the amount required for irrigation, and also the amount of water that could have runoff up to that date."

The heavy diagonal lines are drawn through those record years, as plotted, that most nearly fill the condition of being extreme cases, the other years being disregarded in the construction of the curves.

In the letter of July 2, 1943, Mr. PAGET continues as follows:

> "Referring to Figure 5: The position and slope of the superimposed diagonal lines are determined by the critical black points. The lines are put on to fit the worst conditions. The solid black circles marked by the numerals were first plotted and then the diagonal lines superimposed to fit. The actual slope of the lines does not matter much since in this study it is only their intersection with the heavy line through the points at the extreme left that are considered when using the curve. The same remarks apply to the vertical superimposed lines of Figure 6."

It is considered that by the presentation of Figures 5 and 6, their construction having been clarified, this report will be a worthwhile addition to the working technique of the stream-flow forecaster.

H. P. BOARDMAN (Nevada Cooperative Snow-Surveys, Reno, Nevada)--This paper is very interesting and, I think, makes a strong case for snow-surveys as an aid in flood-control where one or more reservoirs of considerable capacity are available.

The graph on Figure 1 shows excellent harmony between the actual unimpaired or natural flow and the snow-survey water-content corrected for precipitation during April. No statement is made as to whether the indicated snowpack water-content for each year is an average of those for all snow-courses or is obtained by weighting them according to altitude-zones, or by some other system.

It is noted, by examining a recent California Cooperative Snow-Surveys report, that the Kings River Basin snow-courses, numbering 21, range in altitude from 5,500 to 11,400 feet and that of the 19 whose normals have been established the average of April 1 water-content normals for courses from elevations of 9,000 feet up is 38.1 inches, from 8,000 to 9,000 is 33.9 inches, and below 8,000 is 23.7 inches. The straight average of all 19 course normals is 31.7 inches which is somewhat under the water-content value where the normal flow-line intersects the adopted curve. The average of normals for the mid-zone, 33.9 inches, checks very close to this intersection. Also a fair curve for the uncorrected points of April 1 would intersect the normal discharge-line at about the same water-content value.

Since of the 19 snow-courses there are seven from 9,000-foot elevation up, seven below 8,000 feet, and five in the intermediate zone, the straight average might seem to give a good representative water-content value for the whole basin, but if the combined areas of the middle and upper zones are more than twice the lowest zone-area, that should raise the value of the whole basin normal above the straight average of all 19 normals.

Of course, some years the snowpack is not the same proportionately over the whole basin; for instance, this year, 1943, the zone below elevation of 8,000 feet averages more than 25 per cent lower in percentage of normal than the higher zones.

The three Kings River precipitation-stations listed in the above snow-survey report are at elevations 6,775, 1,300, and 500 feet, so there might be some question as to the quantitative correction to apply to the snow-water content of April 1, on account of abnormally high or low precipitation during April at these low-altitude stations, to obtain points for the adjusted graph for May 1.

However, I think enough has been said to show that for this basin the snow-surveys afford a very good criterion for estimating the runoff during April to July.

Figures 3 and 4 show a very good correlation between distant valley temperature and the runoff resulting from an evidently nearly parallel temperature at the snow-fields, with a natural lag of a few days between a temperature high or low and the corresponding high or low runoff-rate. This relationship holds as long as there is sufficient snow left to have a pronounced effect on the runoff, even for several weeks after the peak-flow has been passed in the case of the year 1938. The lag as seen on Figure 3 seems to be less at times of high discharge than at low stage probably because of greater velocity of flow, requiring shorter time for the effect to travel down to the gaging-station.

The correctness of the statement in the third paragraph under "Water-conservation considerations" is not clear to me. For instance, referring to Figure 5, assuming total runoff during April to July to be 2,000,000 acre-feet and that, case 1, the flow does not fall below 10,200 second-feet until July 9 (similar to the year 1911) or, case 2, that with the same total during April to July of 2,000,000 acre-feet the flow drops to 10,200 second-feet by June 16. In the second case the peak-flow would probably be passed considerable earlier than in the first case. The danger of flood-rains would probably be passed by the middle of May. In order to be sure and have the reservoir full at the latest practicable date, could not the filling be started at a later date in case 1 than in case 2? Something would depend on the low point in the reservoir from which filling would start. But in case 1 where the flood-flow lasts until July 9 there should certainly be more remaining acre-feet left to flow after June 16 than in case 2. Then why should it be necessary to start filling earlier in case 1?

Such great difference in time of falling below the flood-stage would naturally be due to effect of temperature. Assuming normal spring precipitation in both cases, the shape of the thermograph would determine the shape of the hydrograph as in Figure 3. That being the case, if strongly sub-normal temperature occurred in April and May indicating delayed melting and runoff, would that justify early filling of the reservoir if snow-surveys had given assurance of ultimate total runoff?

As a matter of fact, I believe that prolonged sub-normal temperature, -5° F or more, during May will result in some actual loss of surface-runoff.

The graphs of Figures 7 and 8 for hypothetical operation of the Pine Flat Reservoir for the year 1938 look reasonable, both leaving the reservoir full at the end of July, which should be expected in a high year as was 1938.

SOME ACCOMPLISHMENTS IN SNOW-SURVEYING

W. W. McLaughlin

Snow-surveying, as it is now understood, means a determination of the amount of water stored in the mountains in the form of snow and ice. The depth of snow and its compactness are incidental factors not essential in attaining the main objective.

The measurement of snow for the purpose of estimating the amount of water that would result from its melting has been made use of at various times for a long time. During the past 30 to 40 years occasional determinations of water-content of the snow have been made by means of melting samples. The so-called "stake" method of snow-surveying and the melting of snow-samples have been replaced by the present method known as the "course" method. In this latter method samples of snow are taken, by means of a hollow tube, through the full depth of the snowpack at approximately the same place each year and year after year. The core of snow is of such diameter that one ounce in weight of snow is equivalent to one inch in depth of water. In other words, the melting of the snow-samples is replaced by weighing the samples and the conversion of this weight directly into water-content.

Prior to the winter of 1935-36 snow-surveying by the course method was in progress in

California and parts of Nevada and Utah, with local measurements in two or three other western States. As of July 1, 1935, the Federal Congress authorized the Division of Irrigation of the United States Department of Agriculture to coordinate and extend snow-surveying and the forecasting of irrigation-water supplies to all western States. For the past eight years such coordinations and extensions of snow-course measurements into the eleven western States have been progressing, and cooperation has been effected with the western Canadian provinces. Exchange of data as between States and with Canada has been most effective. A picture of the general accomplishments to date shows that in the western States there are now 829 dependable snow-courses. There have been almost 1,000 courses, but the elimination of those which appeared to be unnecessary has reduced the present active number to 829. The number of measurements on each course averages at least 15, or about 12,500 measurements in all. There are 177 active cooperators with a minimum number of five in one State and a maximum of 28 in another. The snow-courses are measured three times each year in some States, four times in others, and five times in still others, complete measurements being made February 1 and April 1. Releases of snow-survey and water-supply information are made from two to five times in each State each year. There were 153 radio broadcasts this past year, giving information on water-supply and snow-conditions. In addition, information is furnished to the local presses and for release in Washington by the Federal Government. This past year there were 966 individuals who took part in snow-surveying as of February 1 and again as of April 1. The snow-surveyors have at their disposal 266 shelter-cabins, and of these 77 are owned by the Government. We stock with food, bedding, stoves, cooking utensils, et cetera, 115 shelter-cabins. Many of the snow-courses are so located that they are readily accessible to roads that are kept open during the winter, or near habitations where food and shelter are obtainable.

Prior to 1935-36 the equipment used in snow-surveying in the different States was of sizes, materials, and workmanship that accorded with the wishes of the State or local leaders. In some States there were from two to four different-sized snow-tubes made of steel, aluminum, or other materials. The water-content of the snow was determined by melting a sample and by weight and then converting the weight of snow into its equivalent in water. Under these conditions the data obtained in different States and in some cases within a single State were not interchangeable. One of the first efforts of the Division of Irrigation was to standardize the snow-tubes as to size and material so that equipment and data obtained from its use were interchangeable. Today all snow-tubes are made of duraluminum of the same dimensions, and the sections are interchangeable not only upon the same snow-tube but on any other snow-tube. There are two styles and sizes of scales--the tubular type first developed in Utah and the dial type developed in Nevada. However, since the units of weight are identical, the data are interchangeable. Each of these types of scales has its advantages and its disadvantages with respect to the other, and for the most part selection of one type in preference to the other has been decided on the basis of respective cost and weight.

High mountain ranges are often the source of streams that flow in opposite or nearly opposite directions and frequently into different States. In many instances, snow-survey data are obtained on both sides of these mountain ranges by a single snow-survey party, that is, within a State, and the results of these snow-surveys are sent to the proper State agency for forecasting the runoff. Frequently it is much easier for a snow-survey party from one State to make the snow-surveys in a part of another State. For instance, crews from Idaho, Montana, and Utah measure the snow in parts of Wyoming, but the main survey job is accomplished by Wyoming snow-survey parties.

In these days when aluminum and other critical materials are difficult if not impossible to obtain for snow-tubes, scales, and other equipment, there has been worked out an exchange of existing equipment which has enabled the work to be carried on up to the present time without too serious difficulties.

The first drought-conference, called as much as two to three months prior to the occurrence of the drought, was assembled in Utah in 1934 as the result of snow-surveys which indicated an extremely serious deficiency in the snowpack. The drought was not confined to Utah but extended to almost every western State, which stimulated inquiries from them relative to the prospective water-shortage. As the result of these deliberations, Federal and State funds were made available for the purpose of alleviating as far as possible the drought in Utah, Idaho, and Nevada. The extremely dry years of 1934 and 1936, coupled with the somewhat prevalent sub-normal snowfall for the seven-year period beginning in 1934, focused public attention upon the importance of knowing as much as it is possible to learn of the prospects for the season's water-supply in sufficient time to outline the season's agricultural program to conform to the water-supply. I think it is safe to say that as a result of snow-surveying on the intensified program beginning with the winter of 1935-36 there is hardly a person in the western United States interested at all in the utilization of water who does not look forward to our forecasts.

The forecasting of the water-supply of the West is a tremendous job and worthy of the combined efforts of all agencies that can contribute to the undertaking. It is believed also that when a person contributes to a program, whether it be much or little, he takes an intimate interest in it; and this has proved to be so. The Act of Congress setting up the snow-survey work had in mind a cooperative effort, for it provided that the Division of Irrigation should coordinate and extend existing snow-survey work. The policy of cooperation has been followed with very good results. At the last group meeting in Portland for the purpose of forecasting water-supplies in the Northwest, there were present as active participants from 50 to 75 persons, all extremely interested in contributing whatever they could to make the forecast most accurate and usable. As indicated in the forepart of this paper, there are this year 177 active cooperators contributing money, equipment, and time to the common cause.

When the so-called Mount Rose, later called the course-method of snow-surveying, was first advocated, its practicability and its accuracy were questioned, but in the past 30 years or more, it has demonstrated its utility and has produced reasonably accurate results in almost all cases. Today it is accepted as the standard method in each of the western States, although it is recognized that some of the natural factors affecting runoff from snowpack are not yet evaluated. For instance, the nature of the material that composes the earth-mantle on the watershed, together with its depth and topography, affects the capacity of the watershed to store the melting snow. The percentage of moisture in the earth-mantle is another prime factor influencing the runoff. We have made progress in our investigations into evaluating these factors but have still much to learn about them.

It is astonishing that such a variety of commercial and agricultural interests are concerned with water-supply forecasts, especially when a shortage of snowfall exists. We have inquiries from financial institutions, mercantile companies, eastern wholesale houses, power-companies, mines, municipalities, navigational interests, agriculture--including lumbering and stock raising--and many others. Many of the sugar-beet companies defer their acreage-contracts until the water-supply forecasts are made in order to guard against over-planting in relation to the water-supply available in the late irrigation-season.

Since so many persons are called upon to make snow-surveys each year entailing long and hard trips most of which may be accomplished only with snowshoes or skis, the safety of these men while engaged in this work is one of our first considerations. Certain rules have been promulgated. For instance, the men are not to venture out during periods of storm, and they are not to traverse known or expected snow-slide areas during the critical snow-slide period. The best of equipment is provided in the way of snowshoes and skis, proper clothing is prescribed, and as rapidly as possible cabins are being built where other shelters are not available. Where these cabins are not accessible to habitations, they are stocked with sufficient food and other supplies for a party of two persons for at least two weeks, and in some isolated areas a supply of four weeks for two men is stocked. The distance between shelter-cabins is determined by the terrain and the difficulty of travel. Emergency first-aid kits are also provided, and instructions are given as to their use. General methods for treatment of frost-bite, the prevention of snow-blindness, et al, are also outlined.

In recognition of the air-travel incident to military operations and by commercial air-lines, these shelter-cabins have been made available to the armed air-forces and to the commercial air-companies. On the inside and outside of the door of each shelter-cabin is a map indicating the nearest habitation and highway and directions are given on how it may be reached. One such map was the means of guiding to safety a party from a plane that was forced down in the wilds of Idaho. In another instance this past season, cabins were made available to searching parties in quest of planes that had been forced down.

Shelter-cabins are just what the name implies, that is, places where the snow-surveyors will find shelter and food. Summer homes are utilized when they are advantageously located, of course with the consent of the owner. Frequently mine buildings, lumber camps and sawmills, Forest Service and Park Service buildings, and such other structures as may be available are used. When no suitable building can be secured a cabin is built by the Division of Irrigation, either alone or in cooperation with the Forest Service. The material for construction is, for the most part, logs and other materials found locally, and only such material as can not be found in the hills is imported. One of the first experiences which has a marked influence on the design of cabins where the snowfall is deep was the difficulty of two of our snow-surveyors to find a cabin which they had helped construct. Some 18 or 20 feet of snow had completely covered the building, and only after what seemed to be hours of probing with the snow-tubes did they finally locate it. You can imagine the difficulty the men had in digging down and obtaining entrance through the door to the cabin. We now

provide what is known as the Santa Claus chimney, which is in fact a shaft extending high enough above the cabin so as to be above the snow at all times, with doors that permit the men to enter the chimney and ladders that let them descend into the cabin. Another experience that almost resulted in the snow-surveyors having no food in the cabin was caused by porcupines eating their way through the wooden Santa Claus chimney and helping themselves to as much of the food as they could tear into. Suitable safeguards are now made to prevent recurrences of this kind. The cabins are stocked with food and other supplies in the summer and fall and are inspected each season. Food is left in shelter-cabins not longer than two years, and it is either replaced or used. Canned goods are protected by coating them with shellac. There has been little molesting of shelter-cabins as people realize the importance of these havens of refuge in the protection of human life.

One of the real difficulties that is much accentuated at the present time by the shortage of man-power is means of travel to out-of-the-way places. Snowshoeing is difficult and time-consuming. Therefore, some means of power-locomotion over mountains and canyons is most desirable. Two general types of power-driven transportation facilities are available; one type is the tractor, and the other the toboggan. Varying conditions of snow-cover make it difficult and in many cases all but impossible for locomotion by either of these means of travel. Fresh-fallen snow in very cold weather is fluffy and has little supporting power, and ski and propeller types of transportation bog down. In very cold weather the runners of the propeller-driven toboggan freeze to the snow and are very difficult to start. On crusted snow and steep side slopes, runners do not cut into the snow and the direction of travel may be sidewise down the slope rather than across it. Likewise when the snow is melting in the middle of the day a toboggan may settle so far into the snow that it is unable to push ahead through the snow.

To overcome most of these difficulties the Utah Agricultural Experiment Station and the Division of Irrigation adopted the tractor-type of snow-mobile. One of the first difficulties encountered was packing of snow on the inside of the track, sometimes breaking it. Likewise there is difficulty in guiding, for when one track stops and the other moves forward the latter tends to dig down into the snow. In the shops of the Utah Agricultural College a snow-mobile was constructed from scraps obtained in used-car lots. The results so far have been quite satisfactory. In a recent letter, Dean Clyde of the Utah Agricultural College writes: "I am convinced that this type of snow-transportation will successfully meet most of the conditions encountered in our snow-surveys, especially where the route follows a road or where the country is open so that close timber does not prevent passage. I believe that with the return of peace, when strategic materials again become available for research, this machine can be developed into an inexpensive, light but successful means of transportation on snow-cover."

We have had considerable experience with the motor-propelled toboggan. In writing of the experience the report reads: "The first time the machine was used was February 1. A heavy snow-storm had occurred a few days before the trip and was still in progress during the trip. After we had covered about two-thirds of the distance the loose, powdery snow reached a depth of about two feet. We had to lower the track about this distance below the toboggan and the effect was that we were unable to guide the machine. Whenever the road sloped sideways to any degree we could not keep the toboggan in the road. The work of getting off into the snow and pulling the machine into the proper position became so arduous that we finally abandoned it and made the rest of the trip on skis. The next trip was made on March 1, and at that time the snow was firm and we had absolutely no trouble making the entire trip on the toboggan."

Two years ago a propeller-type toboggan was used in the Jackson Hole country very successfully with the result that within two days a survey-party had accomplished work that had previously required eleven days.

Consideration has been given to the use of the airplane in making trips to out-of-the-way snow-courses. So far, however, we have been unable to locate suitable landing-fields close enough to the snow-courses. We are hopeful that some day we may be able to use the helicopter.

As a part of our research in snow-surveying we have given attention to various methods sugtested for forecasting the ensuing season's water-supply. Some of these methods work successfully where the snowfall is about the same each year, but are not reliable at all where there may be a sub-normal precipitation one year and an above-normal high snowfall the next year. One of the methods to which we have given considerable attention and are still studying involves use of the stream-runoff for certain of the preceding months of the fall, with incorporation of certain snow-survey data. About 75 per cent of the time we have been able, with reasonable accuracy, to forecast the coming season's water-supply, but when the mark is missed there is no question about its being muffed. In some instances there may be a variation of nearly 100 per cent, but most

frequently it will be 30 to 60 per cent, which, of course, is not much better than a guess. Attention has also been given to a comparison to ground-water elevations and the flow of natural springs as indices of what may be expected the ensuing year. Probably the greatest value of comparison of the flow of springs is to indicate the probable moisture-condition of the soil-mantle on the watershed. Other methods have been tried, and we are still testing suggestions as they are presented.

The forecasting of water-supply based on snow-measurements has received much attention, and in the Northwest and in Idaho, as well as to some extent in Colorado, Wyoming, and New Mexico, we have committees of people familiar with local conditions who assist in making the final forecasts.

Interest in this forecasting is extremely keen by those taking part. When a sizable error occurs, as it sometimes does in a forecast, it is the effort of everyone of the committee to find the explanation. This has resulted in ironing out many troublesome factors. Finally, each year we attempt to hold a conference of our survey-leaders from each State to discuss problems that arise through experience and for the general exchange of ideas among those actually guiding the snow-survey work.

It is not my purpose here to give many of the results of our forecasting, and we must keep in mind the fact that these forecasts predict only the amount of water which will be derived from the snowpack, assuming there is a normal precipitation during the spring months, that is, from April 1 to July 1. I can, however, give you an example or two. A year ago we were asked by the State officials of New Mexico to forecast the total runoff of the Upper Rio Grande into the Elephant Butte Reservoir. There was considerable river-rectification work in progress between the reservoir and El Paso; and if there was to be much of a spill from the reservoir, protective measures would of necessity have to be undertaken. Also, it was desired to have the reservoir full at the end of the spring runoff and meanwhile to release as little water as possible. To accomplish this end it was necessary to prevent an excessive amount of water from going over the spillway. Our forecast of the filling was 1,941,000 acre-feet. This forecast was made June 16, and late in August the Bureau of Reclamation office at Denver informed us that the actual peak-fill occurred July 4, at 1,938,000 acre-feet, a difference of only 3,000 acre-feet. Between June 16 and July 4 there was practically no rainfall, which accounts in part for our ability to forecast so accurately.

We made forecasts on the Columbia River at the time the Army Engineers were engaged in construction work in the vicinity of The Dalles, and we were able to predict the flow closely enough so that unnecessary protective work was avoided, as was also danger of excess water. In 1942 from April 1 to September 30, we predicted 70,000,000 acre-feet and the actual flow was 84,800,000 acre-feet. You will recall that the spring of 1942 was the occasion of much rain along the lower Columbia. Our forecasts of the flow of the river at Birchbank, British Columbia, for the period April 1 to September 30, and the actual flow in acre-feet, in round numbers, have been as follows:

Year	Forecast, acre-feet	Actual, acre-feet
1940	39,000,000	37,160,000
1941	35,000,000	32,264,000
1942	35,000,000	Actual figure not yet available
1943	41,000,000	?

Finally, and in order to make the forecasting of the season's water-supply as complete as possible, there has been injected into the information given in our forecasts for April 1 the amount of water carried over in storage in the more important and in many of the smaller reservoirs in each State. Also inaugurated this year has been an effort to indicate the available water in underground reservoirs. This will give a complete picture of the total water-supply.

U. S. Department of Agriculture,
Division of Irrigation,
Berkeley, California

DISCUSSION

GEORGE H. CANFIELD (District Engineer, United States Geological Survey, Portland, Oregon)--The present procedure of making snow-observations and forecasts in this area is based on observations of snow-water storage made at courses at the beginning of each month from January to April. The Water Resources Review issued by the Geological Survey at Washington, D. C., for the six-months' period October 1, 1942, to March 31, 1943, contained a summary of water-contents

of snow and forecasts of runoff. This report indicated that in the northeastern part of the country some forecasts were based on water-content of snow at time of maximum accumulation. It has occurred to me that it may be desirable in this western area to attempt to determine the time of maximum water-content of snow at a few selected courses. This maximum accumulation might occur within a winter or spring month and not be disclosed by the monthly observations. For lower altitudes in Oregon and in the Columbia River Basin, this time of maximum accumulation might occur in February or March and, at higher altitudes, sometimes as late as the middle of April.

I believe observations near the middle of March would be particularly desirable at a few representative stations, particularly at those below an altitude of 4,000 feet. I appreciate that, because of present shortages of labor, this additional work cannot be now undertaken. But in the future it might well be an objective to obtain two or three observations each month from February to April at a few key stations at various altitudes in order to more certainly determine the time and amount of maximum water-content in the snow-cover. Has anything been done along this line in this area by the Soil Conservation Service?

That's all I intended, an attempt to suggest at this time that at some future date, at a few selected courses, more frequent observations be made during those critical months of March and April.

In answer to Mr. McLaughlin's question why 4,000-foot elevation was chosen, I am thinking that at the lower altitudes in the Cascade and Coast ranges there might be an addition to the snow-cover during the first half of the month of February or March, with no snow on the ground at end of month. Also courses below 4,000 feet would be more readily accessible for additional visits and snow-measurements. It would be desirable to extend these more frequent snow-observations at a few key stations at all altitudes.

In the Blue Mountains, as was suggested by Mr. Work and Mr. Marr, some of the runoff from snow-melt may occur during the middle of February from the Silvies River and other streams in that area. The maximum discharges on most streams draining the Blue Mountains this year reached their peaks about the middle of April; that on the Crooked River near Cove occurred at the beginning of April. Because of the cool spring the runoff has been later than usual this year.

R. A. WORK (Irrigation Engineer, United States Division of Irrigation and Oregon Experiment Station, Medford, Oregon)--I think Mr. Canfield's suggestion is well based for this reason: We tentatively have found that on many streams in Oregon the best estimate of snow-melt runoff is often developed by use of the maximum snow-accumulation figure for the winter regardless of whether that accumulation occurred during the middle of February or at the first of May. To that extent Mr. Canfield has substantial argument to back his proposal, but on the other hand we are distinctly limited in the making of such frequent observations by some of the factors that Mr. McLaughlin has spoken of, such as shortage of funds and personnel, difficulties of transportation, inaccessibility of these places, and so forth. I will go on record as concurring most heartily with Mr. Canfield's suggestion concerning need of more frequent observations.

BERTRAM S. BARNES (Regional Engineer, United States Weather Bureau, San Francisco, California)--Mr. Codd has assumed that all of us know that a snowflake is composed of little hollow tubes. You can have two snow-crystals that look very much alike when seen side by side, yet actually they may be widely different. One may be practically filled with water and the other might be filled with air. In other words, you would have one dry and one wet flake and find that externally they would appear to be the same. The difference is in the "quality" of the snow. There is, therefore, a variation in the number of British thermal units required to melt a given weight of snow.

PRECIPITATION-RUNOFF RELATIONSHIPS AS A BASIS FOR WATER-SUPPLY FORECASTING

George D. Clyde and R. A. Work

Early history of snow-surveys--Measurements of snow-water content have been made by scientists and others for more than 40 years. The earliest reported measurements were made by CHARLES A. MIXER at Rumford Falls, Maine, in 1901. Mixer used a tube to cut out a sample of snow which he weighed to determine its water-content. Later, in 1903-1904, ROBERT E. HORTON at Utica, New York, developed a tube for cutting snow-samples and these samples were weighed to determine the water-content. Horton's tube was 5.94 inches in diameter and five feet

long. Subsequent to the work by Horton in New York, the record shows that in 1907 J. C. ALTER, an employee of the Weather Bureau in Utah, proposed to the Utah State Engineer that measurements of mountain snow-cover be made. Four years later the United States Weather Bureau gave its support to snow-cover measurements and, in 1911, Alter made the first official survey of the water-content of the snow-cover on Maple Creek Watershed in Utah County. "About 2000 depth-measurements were made and 277 actual determinations of water-content were completed, using the Marvin snow-density tube and weighing-scales" [J. C. Alter, Trans. Amer. Geophys. Union, pp. 892-899, 1940]. Similar measurements were made in 1912 and in 1913.

During the same period that Alter was making his measurements in Utah, J. E. CHURCH, JR., University of Nevada, was making similar measurements in the vicinity of Lake Tahoe. Dr. Church began his work in 1909 with the development of a sampling-tube and weighing-scales that would permit quick sampling of deep snow. He was at this time studying the relationship of forests to conservation of snow. While conducting this study, Dr. Church conceived the idea of using the accumulated snow-cover as a basis for forecasting stream-flow, and to him should go the title "Father of Snow-Surveying and Stream-Flow Forecasting"

Snow-survey courses were extended around Lake Tahoe in 1911, and in the following years cooperative relationships were worked out with power-companies, the United States Bureau of Reclamation, and the State of California to further snow-surveying and the forecasting of stream-flow. During the period 1911-1923 extensive snow-survey networks were established in Nevada and California.

For several years prior to 1914, the United States Weather Bureau published in its Climatological Data for Utah a general statement of snow-cover conditions. The following statement is taken from the issue of February, 1913: "The large amounts of snow which fell in the Utah area during February insured a good average supply of water for the great Salt Lake and Sevier Lake watersheds. The snow was reported as having drifted well and packed solidly."

Such reports had little value because of their extreme general character, but in 1914 a cooperative agreement entered into between the Weather Bureau and the United States Forest Service provided for installation, on the forests at selected points, of standard Weather Bureau snow-stakes. These stakes were graduated in inches and were 90 inches high. Many of these stakes were located in such inaccessible areas that three or four days were required to reach them and return. Such trips were difficult and hazardous. As a result, many of the stakes were abandoned and the readings on others were intermittent. Water-content measurements were made at several of the snow-stakes, but, for the most part, depth-measurements only were made.

CLYDE [Snow cover measurements in Utah 1914-1929, Hydraulic Eng., December 1929] makes the following statement: "The water-content of the snow-cover and not depth alone must be determined if the snow-cover is to be used as an indicator of runoff." All of the snow-stake records in Utah were analyzed to determine the stake reading-runoff relationship. No relationship was found and it was therefore concluded that measurements of snow-cover as indicated by snow-stake readings were not representative of true conditions.

Snow-surveys patterned after the Church method were started on the Logan Watershed in Utah in 1923-24. In 1930 the snow-survey course network was extended over the entire State and, where possible, a snow-course was established near a Weather Bureau snow-stake. As the snow-course records became available, they were published in place of the snow-stake readings in the monthly Climatological Data sheets for Utah. Snow-stake readings are not snow-surveys and the snow-cover data from the two sources are not comparable. Therefore, when studying the relationship between snow-cover and runoff, snow-stake readings cannot be compared with snow-course data.

J. C. ALTER, in his paper "The mountain snow survey: Its genesis, exodus, and revelation", attempts to show that precipitation-measurements as obtained by Weather Bureau catch-cans offer an adequate and improved substitute for standard snow-surveys in forecasting stream-runoff. In attempting to prove his contention, Mr. Alter selected as an illustration Big Cottonwood Creek near Salt Lake City. A snow-course was established at Silver Lake on the headwaters of this stream, in 1931, but in his analysis Mr. Alter used snow-stake readings near Silver Lake to represent snow-surveys from 1919 to 1930. Actual snow-course measurements at Silver Lake were available subsequent to 1930 only. Consequently, the snow-cover record used by Alter consisted of 11 years of snow-stake readings made in an entirely different exposure and at least 1000 feet distant from the snow-course, and ten years of record on a standard snow-course. Mr. Alter concluded his paper by stating that the per cent accuracy of runoff-forecasts for Big and Little Cottonwood creeks is much higher when the precipitation at valley stations is used than when the

Silver Lake snow-course record is used. In other words, he contends that at least on the Big Cottonwood Creek Watershed, precipitation at valley stations is a better index of runoff than a measurement of the water-content of the snow-cover on the watershed.

It has already been pointed out that the snow-cover data used by Mr. Alter were faulty because he substituted snow-stake readings for snow-course measurements. The writers now propose to show that snow-surveys, properly made and interpreted, furnish a true index of potential runoff, keeping in mind that every watershed is a law unto itself and that abnormal fall and spring precipitation, temperature during melting, and soil-moisture conditions on the watershed affect the basic snow cover-runoff relationships.

Watershed-runoff--Surface-runoff from any watershed is a residual and equals the total precipitation on the watershed, minus the losses from the watershed. This relationship may be written in the form of an equation as follows: $R = (P - L)$.

The runoff can be measured by standard methods at control-stations. The accuracy of such stream-flow measurements may, under ideal conditions, be within five per cent but it is believed that ten per cent would be nearer that reached on most streams.

Precipitation can be measured using standard meteorological instruments. Such measurements, however, are difficult and expensive if volumetric quantities on a watershed are desired. Large numbers of rain-gages would be required and a method of catching precipitation which falls as snow on high inaccessible watersheds would be necessary. No such equipment is available on the watersheds of the West and therefore a quantitative determination of the volume of water falling on a given watershed in a given period is not at present possible.

Losses may consist of evaporation from the snow-cover or earth-mantle, transpiration from vegetation, leakage from watershed, which may be plus or minus, and ground-storage which also may be plus or minus. Evaporation-losses depend on many factors including opportunity for evaporation, vegetal cover, exposure, extent of snow-cover, and amount of soil-moisture. Transpiration-losses similarly depend upon many factors including type of vegetation, extent of vegetal cover, exposure, amount of soil-moisture, temperature, and wind movement. Watershed-leakage depends upon the elevation and geological structure of the watershed. Ground-storage depends upon the extent and thickness of the earth-mantle, the vegetal cover, the permeability of the soil, the slope and exposure, the extent of the snow-cover, and the rate of melting. Few of these factors lend themselves to specific measurement. Therefore, water-losses are more difficult to determine quantitatively than either runoff or precipitation.

On a given watershed the topography, vegetal cover, earth-mantle, geological structure, and location with respect to prevailing air-movements are fixed. Therefore, the losses or gains which are functions of these factors should be quite constant.

The evaporation from vegetal cover and the earth-mantle will vary somewhat with the presence or absence of soil-moisture. For example, evaporation from the soil cannot take place if there is no water in the soil to evaporate. Similarly, if soil-moisture is deficient, transpiration-rates from vegetation will be reduced. If the areal extent of the snow-cover is small, the total evaporation from the snow will be small, other conditions remaining the same.

The time of occurrence of precipitation, the form in which it falls, and the temperature all affect materially the runoff-yield per unit of precipitation. In western regions where irrigation is essential to agriculture, the precipitation is not distributed to coincide with the needs of the growing plants. Most of the precipitation falls during the dormant season and in the form of snow which accumulates on the high watersheds and constitutes the potential water-supply for the following season's runoff. The yield from this accumulated snow-storage is affected by water-losses during both the accumulating and melting periods. It is these losses that are variable on a given watershed and it is these losses which affect the forecasts of runoff based on snow-cover.

Except for power-generation, the period of greatest need for water in the arid West is during April to September. Water-users, therefore, are most interested in the probable supply during this period. The most important single factor affecting stream-flow in the arid West is the accumulated snow-cover on the high watersheds. This snow-cover is measurable at representative points so that an index of snow-cover can be obtained. This index applied to the runoff provides the snow cover-runoff relationship for a given watershed. This relationship must be considered as basic and subject to modifications as indicated by abnormal conditions of precipitation before and after the snow-accumulation period, abnormal temperatures during melting, abnormal distri-

Table 1--Comparison of precipitation at Joseph, Oregon, with subsequent stream-discharge in the Salt Lake City Area

[All values in columns (3), (4), and (5) in per cent of 21-year mean]

Year	Precipitation October to March		Discharge Big Cotton-wood Creek	Differ-ence (4) - (3)
(1)	(2)	(3)	(4)	(5)
	inch	pct	pct	pct
1918-19	8.96	106	91	-15
1919-20	10.50	124	137	+13
1920-21	16.06	189	181	- 8
1921-22	9.66	114	154	+40
1922-23	8.01	94	139	+45
1923-24	8.09	95	74	-21
1924-25	8.30	98	102	+ 4
1925-26	5.81	68	87	+19
1926-27	7.52	89	124	+35
1927-28	8.90	105	98	- 7
1928-29	7.87	93	115	+22
1929-30	9.28	109	71	-38
1930-31	6.80	80	50	-30
1931-32	10.18	120	107	-13
1932-33	9.49	112	97	-15
1933-34	7.04	83	31	-52
1934-35	6.12	72	83	+11
1935-36	6.76	80	103	+23
1936-37	6.50	77	83	+ 6
1937-38	10.19	120	104	-16
1938-39	6.21	73	69	- 4
Mean	8.49	....	....	20.8

bution of snow-cover with respect to elevation, and the areal extent of the snow-cover during the spring precipitation-period.

The contention advanced by Mr. Alter [Trans. Amer. Geophys. Union, pp. 892-899, 1940] that precipitation at valley stations, either on or off the watersheds, may furnish a better index of run-off than the measurement of accumulated snow-cover on the watershed, is neither logical nor sound, but purely a matter of chance. Mr. Alter said, in part: "Now, here is the final point in this paper: The Salt Lake City precipitation-record made 25 miles to the northwest of Silver Lake Basin and ten miles from the nearest edge of the watersheds, when used as a forecasting figure, shows an average error of 17 per cent, or one per cent better than the snow-survey figures."

As a matter of curiosity, and using Mr. Alter's method of analysis, Table 1 was prepared; this shows that the precipitation at Joseph, Oregon, a location climatically different and a great distance from the Cottonwood, Utah, drainage is only slightly less accurate as an indicator of Big Cottonwood discharge over the 21-year historic period than either the mixed snow-stake and snow-survey readings or the accumulated precipitation at Silver Lake on the headwaters of that very stream. Mr. Alter shows the average deviation from the mean of forecasts based on the precipitation at Silver Lake to be 17.0. The average deviation of a water-forecast for Big Cottonwood Creek, Utah, based on precipitation at Joseph, Oregon, is only 20.8 for the 21-year period.

Furthermore, the precipitation at Joseph, Oregon, was a better indicator than the precipitation at Salt Lake City in ten out of the 21 years, even though Joseph, Oregon, is 16 times farther distant from the watershed than Salt Lake City and 38 per cent of the time the precipitation at Joseph was as good or better a predictor than the Silver Lake precipitation-station itself.

Does this mean that the precipitation at Joseph, Oregon, can be used almost as effectively as snow- or precipitation-measurements at the head of Big Cottonwood Creek, Utah, to predict the flow of that stream? A more logical conclusion would be that precipitation at valley stations either on or off the watershed, have only a chance relationship to the runoff from a given watershed.

Snow-surveys--Recognizing the impracticability of exactly determining volumetrically the precipitation on a given watershed or the water in a given snow-cover, a method of making snow-

Table 2--Relationship between snow-cover, precipitation during April to May, and runoff from Big Cottonwood Creek, Utah

Year	Water-content, Silver Lake (elevation 8725 feet)		Water-content, Mill D Fork (elevation 7400 feet)		April to May departure from normal prec. Silver Lake	Correction applied to Silver Lake water-content[a]	Corrected water-content Silver Lake (2) + (7)	
	Depth	Average	Depth	Average			Depth	Average
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	inch	pct	inch	pct	inch	inch	inch	pct
1931	13.0	56.3	.....	.....	-1.60	-2.40	10.60	50.0
1932	30.1	130.3	.....	.....	-1.97	-2.96	27.14	128.0
1933	25.0	108.2	.....	.....	+1.07	+1.07	26.07	123.0
1934	16.4	71.0	.....	.....	-5.90	-8.85	7.55	35.6
1935	21.0	90.9	.....	.....	+1.75	+1.75	22.75	107.3
1936	35.5	153.7	.....	.....	-2.30	-3.45	32.05	151.2
1937	24.7	107.0	19.9	107.0	-0.45	-0.68	24.02	113.3
1938	26.7	115.5	18.8	101.0	-1.26	-1.89	24.81	117.0
1939	20.5	88.7	17.3	93.0	-3.43	-5.14	15.36	72.4
1940	18.4	79.6	17.3	93.0	-2.16	-3.22	15.18	71.6
1941	19.9	86.1	15.7	84.4	+1.69	+1.69	21.57	101.8
1942	26.4	114.3	22.4	120.0	+0.96	+0.96	27.36	129.0
Mean	23.1	.....	.....	.....	.....	.....	21.2	.....

Year	April to September runoff		Uncorrected April to September forecast, average Fig. 1	Actual departure uncorrected forecast from Fig. 1	Forecast corrected for April to May prec. departure from Fig. 1	Actual departure from corrected forecast, from Fig. 1
	Amount	Average				
(1)	(10)	(11)	(12)	(13)	(14)	(15)
	a-f	pct	pct	pct	pct	pct
1931	20420	61.6	60.0	+ 1.6	54.0	+ 7.6
1932	42600	128.6	126.0	+ 2.6	123.5	+ 5.1
1933	38200	115.3	106.8	+ 8.5	119.0	- 3.7
1934	12600	38.6	74.0	-35.4	41.3	- 2.7
1935	33710	101.7	91.0	+10.7	105.5	- 3.8
1936	40602	122.5	146.5	-24.0	144.2	-21.7
1937	32668	98.6	105.0	- 6.4	110.5	-11.9
1938	40698	122.8	113.0	+ 9.8	113.0	+ 9.8
1939	27459	82.9	89.0	- 6.1	74.5	+ 8.4
1940	24589	74.2	80.5	- 6.3	73.0	+ 1.2
1941	40437	122.1	86.5	+35.6	100.3	+21.8
1942	43280	130.7	112.0	+18.7	124.5	+ 6.2
Mean	33132	.....	.....	.....	.....	.....

[a]Raw data corrected by adding to the water-content at Silver Lake all plus-precipitation departures for April to May or deducting 1.5 times the minus-precipitation for April to May.

surveys on high watersheds to secure an index to be used as a basis for predicting runoff was proposed by J. E. CHURCH of the University of Nevada. Methods of making snow-surveys have since been further refined by many engineers working in this field.

Snow-surveys do not attempt to determine volumetrically the amount of water in snow-storage on a given watershed. By proper selection of sites for the snow-courses and by making observation of the water-content of the snow-cover at definite and fixed points, year after year, the relationship between the snow-cover index and the runoff from a given watershed for a definite period is determined. Such snow-surveys are not to be confused with snow-stake readings. Snow-surveys provide for enough observations to smooth out variations in measurements due to topography or drifting.

Snow-survey courses must be established at different elevations on a given watershed to define the rate of change in cover with elevation. It has been definitely shown that this rate of change varies from year to year and that water-supply forecasts based on high stations alone have been in error due to excess or deficiency of low snow-cover.

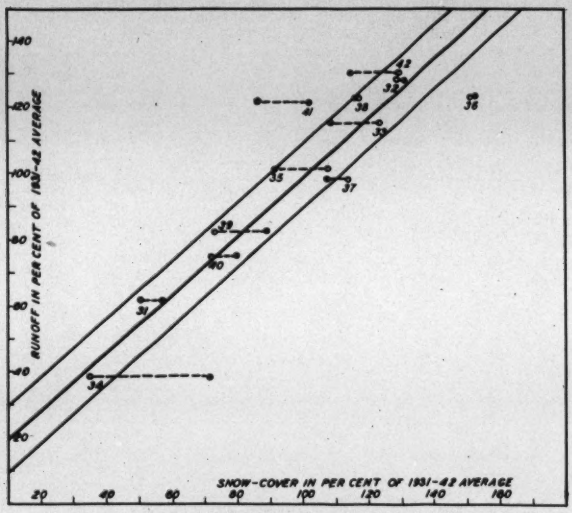


Fig. 1--Relation of snow-cover (S) and runoff (R), Big Cottonwood Creek, 1931-42, R = (0.89S + 10)
(• = uncorrected plotting; ∘ = corrected plotting)
[Average variations: Actual runoff from forecast, 13.8 per cent; after correction for abnormal precipitation during spring and summer, 8.4 per cent]

It is fully recognized that measurement of snow-cover alone is not sufficient to form the basis of an accurate forecast. Supplemental precipitation-records in the fall and during the melting-period in the spring should be made. The forecast for April 1 should be corrected on May 1 and June 1 in harmony with precipitation during those months and the melting-temperatures. Inasmuch as much of the precipitation during April and May, particularly on the higher areas, will be in the form of snow, shielded precipitation-gages should be used to measure this precipitation.

Big Cottonwood Creek near Salt Lake City--Snow-surveys have been made at Silver Lake (elevation 8,725 feet) near the headwaters of Big Cottonwood Creek since 1931, and at Mill D Fork (elevation 7,400 feet) since 1937. Prior to 1931 snow-stake measurements only were made at Silver Lake.

The Big Cottonwood Creek Watershed comprises an area of about 50 square miles and has an average water-yield during April to September of about 45,000 acre-feet. The average yield during April to September for the period 1931-1942 is 33,093 acre-feet. Table 2 shows the relationship between snow-cover and runoff for Big Cottonwood Creek in per cent of the average during 1931-1942.

Table 2 shows also the snow-cover record at Silver Lake and Mill D. It shows the precipitation-departure from normal at Silver Lake for April to May and April to July. It shows also the runoff-forecast for each year in per cent of the average during 1931-1942 and the departure of the actual runoff from the forecasted value. The forecasted value was obtained by plotting the snow-cover against the runoff and drawing a best-fit straight line through the plotted points. Figure 1 shows graph for Big Cottonwood of snow-cover against runoff. Each year's forecast was made by applying to the curve Silver Lake snow-cover expressed as per cent of the average during 1931-1942 and reading off the corresponding values of runoff.

The record at Mill D shows that the snow-cover at elevation of 7,400 feet does not bear a constant relationship to the snow-cover at Silver Lake (elevation 8,725 feet). The excess or defi-

ciency of precipitation at Mill D would, therefore, affect materially the runoff as indicated by the snow-cover at Silver Lake.

The precipitation during April to May also affects the predicted runoff. Table 2 and Figure 1 show that when uncorrected Silver Lake snow-cover was used, the average departure of the actual runoff from the forecasted runoff was 13.8 per cent. After correcting for abnormal precipitation during April and May, the average departure was only 8.4 per cent. The curve (Fig. 1) shows that nine of the 12 years gave a predicted value within ten per cent of the actual. The other three years were apparently affected by abnormally low snow-cover which was not indicated in the Silver Lake cover or by abnormal temperatures during the melting-season.

This analysis shows that an index of runoff based on measurement of accumulated snow-cover, corrected for abnormal precipitation and temperatures during melting and for ground-storage, is rational and logical and that it takes stream-flow forecasting out of the realm of chance and arm-chair prophets and places it on a basis of measurement of fact. Relationships of snow-cover and runoff have been developed for Big Cottonwood Creek which enable forecasts to be made consistently within ten per cent plus or minus of the actual runoff.

Similar relationships are possible for all other watersheds when the major portion of the annual precipitation falls in the form of snow.

Summary--The experience reported by CHURCH in Nevada, CLYDE in Utah, PAGET in California, MARR in Idaho, WORK in Oregon, PARSHALL in Colorado, MONSON in Montana, and FARROW, FRAME, and WEBB in British Columbia indicates that the best basis yet developed for forecasting water-supplies is the index obtained by measuring the accumulated snow-cover at the end of the winter precipitation-season with corrections for ground-water storage and for deviations from normal precipitation and temperature during the melting-period.

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Medford, Oregon

DISCUSSION

RAY K. LINSLEY, JR. (Associate Hydraulic Engineer, United States Weather Bureau, Sacramento, California)--The authors state that a correlation between precipitation at a low-level station and subsequent runoff from a mountain basin is purely a chance correlation. Nature follows an orderly pattern, but we as yet do not thoroughly understand its complexities. Water which appears as runoff in the streams originally reached the basin as precipitation. Thus whenever a correlation can be derived between precipitation and runoff there is more than chance behind it. The storms which bring precipitation to Cottonwood Creek Basin come from the west or northwest, and therefore pass Joseph (Oregon) and Salt Lake City en route. The amount of rainfall deposited at each spot is influenced materially by orographic conditions. A rough proportionality develops which, although subject to wide divergence in individual storms, becomes reasonably constant where considered by yearly periods.

In the flood-forecasting for the Sacramento Valley this normal relationship is being used as a basis for estimating storm-rainfall in isolated mountain areas from which rainfall-reports can not be obtained. A paper by Messrs. LIGHT and KOHLER presented before the April 1943 Meeting of the American Geophysical Union in Washington demonstrates a procedure for estimating seasonal runoff from precipitation-records. They introduced some refinements which ALTER did not use, and found a rather satisfactory correlation for the upper Rio Grande Watershed. I have made a rough application of their method to basins in the San Joaquin and Sacramento valleys of California and to the Clark Fork Basin in Montana and have obtained correlations showing average error of from ten to fifteen per cent of normal.

MERRILL BERNARD (United States Weather Bureau, Washington, D. C.)--In the authors' summary persons are named whose experience is taken as "the best basis yet developed for forecasting water-supplies". The writer believes these men will join with him in the simple, basic premise that any method of forecasting which gives a more accurate, timely, and dependable result will be welcomed at any time and given a change to demonstrate its superiority. There is little to criticize of the snow-survey, as an end in itself; that is, as a measure of the water-content of snow on the ground at the point of observation. As to its being the best, if not the only means of estimating

stream-flow subsequent to the fall and melting of snow, there is, and should be, if we are to progress at all, a reasonable doubt of its sustained superiority in terms of accurate and dependable forecasts. Furthermore, a forecasting service should be supported by procedures that are rational, statistically sound, and depend to minimum extent on personal judgment, an element which is at present rather conspicuous in snow-survey forecasting. This in no way depreciates the necessity for judgment but simply recognizes that there is "poor" as well as "good" judgment and that there is a limit to the accumulated experience within any specialized group as the inevitable "turnover" takes its toll.

The use of the snow-survey as an index, which is understood to be a dimensionless indicator and can have only a statistical meaning, does not seem entirely compatible with the relatively short period for which these data are usually available. However, the shortness of record would not detract from the value of snow-surveys provided the sampling network were sufficiently dense to yield an accurate measure of the volume of stored water over a prescribed basin. Cost, of course, becomes the limiting factor in approaching such an objective in Western mountain areas.

Current studies by the Weather Bureau [see 1 of "References" at end of discussion] are demonstrating the successful application of well-established statistical procedures to the problem of seasonal forecasting. The most important of the several variables entering into the solution is, of course, winter precipitation. If there is justifiable criticism of the earlier precipitation-observations, which admittedly detract from their reliability, there is a compensating and outweighing advantage in the longer record-period they represent. One apparent weakness in the use of a long-period record of precipitation in any statistically developed procedure lies in the fact that all records published under the same station name are not necessarily for the same location and exposure. Moves of stations of a few miles have not in all cases been indicated by a change in the names of the stations. This weakness is indeed only apparent, since it can be overcome by a simple adjustment accomplished by plotting the accumulated precipitation at the station in question with the corresponding accumulated values of mean precipitation for a group of stations within the zone of its environment [1,2]. If significant changes in location of station or exposure have occurred, the mean line through the plotted points will take the form of two or more straight lines intersecting at points representing the years in which the change occurred. Adjustments are then made on the basis of the change in slope of the segments of the broken line.

The significance of record-length [3] is illustrated in Figure 1. The progressive improvement in accuracy and dependability of a regression-line as the length of record is increased, is obvious. Both the slope and position of a regression-line developed from a limited record are subject to fluctuations in sampling. However, the magnitude of these fluctuations is reduced as the number of observations increases. For example, assume that the regression-line computed from the observed data is as shown in Figure 1. If only four years of record were available for the computation, the probability is 93 per cent (corresponding to twice the standard error) that the true regression-line is located in the region bounded by the two curves labeled n = 4. Similarly, for 32 observations, the range of the position of the true regression-line is reduced between the curves labeled n = 32. It can be seen that there is a pronounced improvement in the stability of the regression-line, and therefore in the accuracy of the relationships expressed, with the progressive increase in the number of observations.

The authors' reference to the correlation between the record of precipitation at Joseph, Oregon, and seasonal runoff from Big Cottonwood Canyon in Utah is interesting, and apparently is intended to show that any correlation between precipitation and runoff is wholly accidental. That such a conclusion is wrong is demonstrated in the following analysis. The correlation-coefficient between the runoff during April to July from Big Cottonwood Creek and the precipitation during October to March have been computed from a 21-year record (1919-39) at each of 57 stations. These stations were so selected as to provide a reasonably uniform network within a radius roughly equal to the distance between the basin in question and Joseph, Oregon. The results are summarized in Figure 2 where the correlation-coefficient and elevation for each of the stations have been plotted. An inspection of Figure 2 will reveal that, contrary to the opinion of the authors, a large number of relatively low-elevation precipitation-stations do have a significant correlation with runoff.

In general, as should be expected, there is a progressive decrease in correlation with increasing distance. This is shown in Figure 3A where r, the correlation-coefficient, is plotted against distance from the Big Cottonwood Basin. It is apparent from Figure 2 that virtually all stations located in the outer band, having a relatively high correlation-coefficient, have one thing in common with Big Cottonwood Canyon, namely, aspect. Joseph, Steamboat Springs, Ames, and even Durango, with southern aspect but free western exposure, are all in basins located on the

western slope of ranges that exercise a controlling influence on precipitation through orography. There are, of course, among the 57 stations arbitrarily selected, those that would require a consideration of other factors, such as variation in quality of record, localized physiographic influences, errors of sampling (or accidental errors)--these in addition to aspect, elevation, and distance.

Western mountain snowfall is produced by storms that move in from the Pacific Ocean

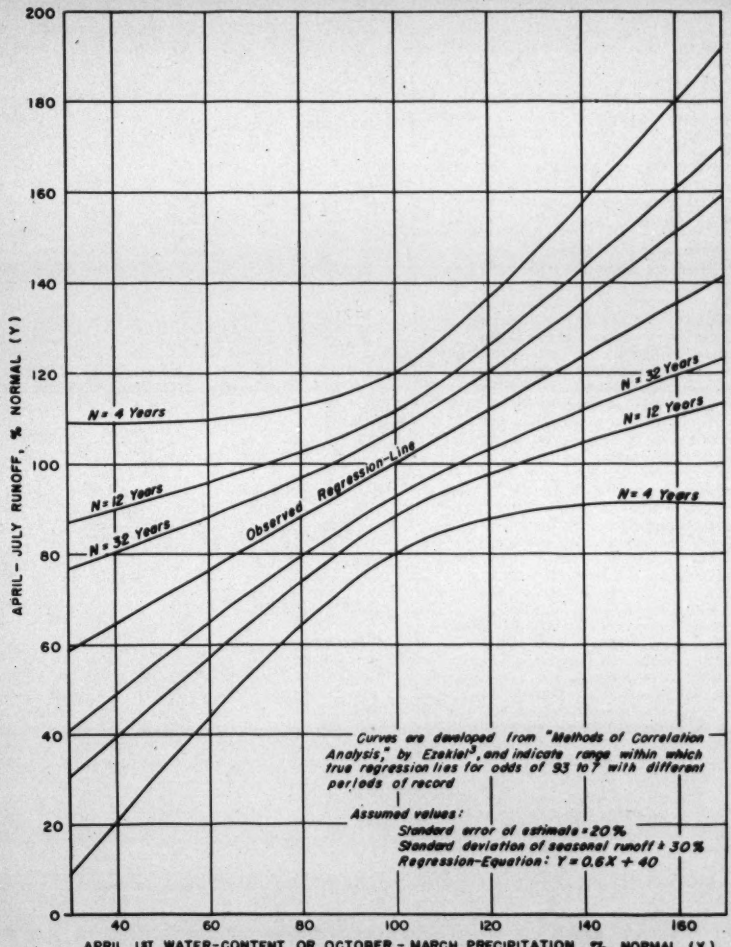


Fig. 1--Variation in reliability of regression-line with length of record

accompanied by wide, southwesterly, moist currents aloft. The moist air-mass, as it precedes or accompanies the storm, is underrun by the colder northwesterly currents as the storm-center moves eastward over the high country. Snowstorms occur first over the Sierra Nevada and Cascade ranges and then move successively over the ranges to the east. The higher of these remove more of the moisture and this removal depends on the elevation of each succeeding barrier. Valleys and leeward slopes between the controlling ranges frequently experience little or no snow, while mountainous sections receive correspondingly greater amounts. Temperature is uniformly low, due to the relatively high elevation of the region, which generally insures precipitation in the form of snow.

But why go to Joseph, Oregon, to forecast the seasonal flow for Big Cottonwood Canyon? Limiting the period of record of the precipitation-station to that of the snow-survey (12 years), and using the runoff-data in the authors' paper, we find a correlation-coefficient of 0.82 between stream-flow and precipitation measured at the Weather Bureau's station, Brighton (Silver Lake) and 0.78 between stream-flow and the authors' uncorrected forecasts for April to September based on snow-survey values for Silver Lake. The correlation-coefficient for the 21-year record of precipitation, while naturally reduced (in this case to a value of 0.79), is still greater than the coefficient for the 12-year snow-survey record. But more important, the final purpose to be served--the forecast--has the benefit of the stability inherent in the longer record. Approximately two-thirds of the variance of stream-flow is accounted for in precipitation as measured by either the snow-course or the snow-gage and one-third by other factors, a number of which are determinable. A multiple correlation that includes these factors will reduce the unexplained variance and improve the forecasting-relation.

The effect of elevation on the representativeness of a station has been discussed by the authors. The approximate relation between the correlation-coefficient and elevation for the 57 stations plotted in Figure 2 is shown as a trend-line in Figure 3B. There is naturally a tendency for an increase in correlation with an increase in altitude up and into the effective snow-producing zone. The curve can be expected to drop, however,

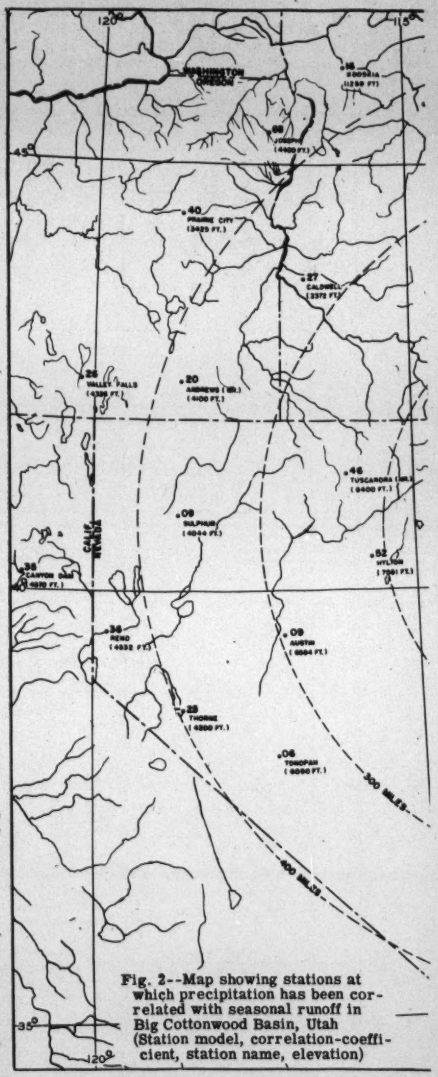
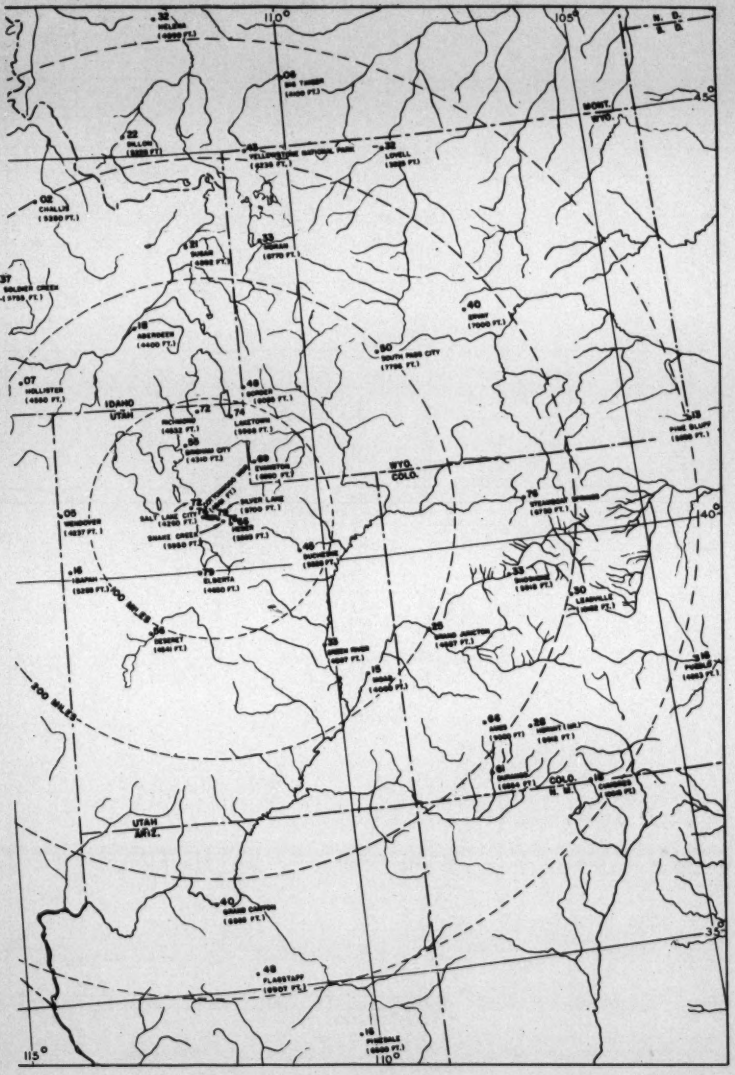


Fig. 2--Map showing stations at which precipitation has been correlated with seasonal runoff in Big Cottonwood Basin, Utah (Station model, correlation-coefficient, station name, elevation)


110°
105°
45°
40°
35°
115°
110°
100 MILES
200 MILES
IDAHO
UTAH
WYO.
COLO.
UTAH
ARIZ.
COLO.
N. M.
MONT.
WYO.
HELENA (4000 FT.)
BIG TIMBER (4000 FT.)
BILLINGS (3600 FT.)
YELLOWSTONE NATIONAL PARK (6250 FT.)
LOVELL (3800 FT.)
CHALLIS (5300 FT.)
SUGAR (4800 FT.)
SALMON (5970 FT.)
GOLDEN CREEK (5750 FT.)
ABERDEEN (4400 FT.)
SPRING (7000 FT.)
SOUTH PARK CITY (7796 FT.)
HOLLISTER (4650 FT.)
RICHFIELD (4832 FT.)
LOGTOWN (5068 FT.)
SPANISH FORK (4340 FT.)
EPHRAIM (6800 FT.)
PINE BLUFF (5000 FT.)
SALT LAKE CITY (4220 FT.)
SILVER LAKE (5700 FT.)
SNAKE CREEK (5950 FT.)
MANTI (5800 FT.)
HUNTINGTON (5850 FT.)
WENDOVER (4237 FT.)
ELSINORE (5900 FT.)
LEADVILLE (9927 FT.)
GRAND JUNCTION (4597 FT.)
MONTROSE (5806 FT.)
DURANGO (6612 FT.)
FARMINGTON (5074 FT.)
GRAND CANYON (6998 FT.)
FLAGSTAFF (6907 FT.)
PINEDALE (6800 FT.)

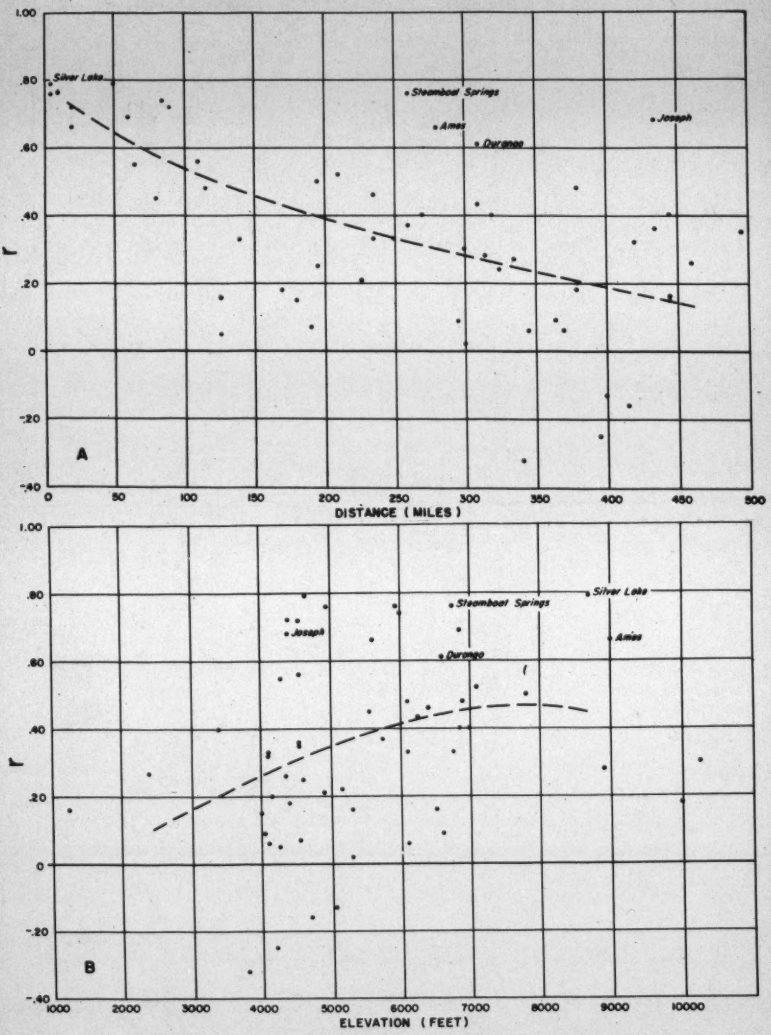


Fig. 3--Effect of distance and elevation on precipitation-runoff correlation

when the Alpine Zone is reached, from which region, in spite of greater depth of snow, little run-off is contributed to valley flow. The range in elevation of the precipitation-index network used in seasonal forecasting for the Rio Grande Basin is from 7,000 to 10,000 feet, on the upper Colorado is from 5,000 to 10,200 feet, on the Green is from 5,000 to 8,800 feet--all with long periods of records.

It is not in accord with known facts to discredit the "Valley Station" as a significant index to precipitation at higher levels. Precipitation-events (storm-periods) have within themselves a unity which expresses itself in a high degree of dependency of precipitation measured at points of different elevation (including those below and within significant distance of the average snow-line), even though the character of the precipitation (rain or snow) is different at the points compared.

Furthermore, winter conditions in the regions of the West producing snow-melt runoff combine to retard runoff from snow or rain with almost equal effectiveness--snow remaining in the solid state until the spring release and rain becoming ground-frost, ice, and temporary ground-water storage--all to be released under spring conditions.

The writer agrees that spring precipitation is one of the variables that must be included in any successful May 1 forecasting-equation. In addition to this factor in the authors' graphical correlation, a variable multiplier for precipitation has been used which depends on the sign of its departure from normal. It should be pointed out that by using this procedure the number of "degrees of freedom" have been reduced by two. Therefore, the brief period of record used has in effect been shortened still further, and the average error of 8.4 per cent obtained by the authors is a highly optimistic estimate of future forecast-verification.

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FORECASTING RUNOFF FOR POWER AND IRRIGATION FROM RELATIVELY LOW-LEVEL AREAS

Harry Olsen and E. B. Price

We have been asked to give a brief discourse relative to our methods in connection with forecasting runoff from the Klamath Basin, located in southern Oregon immediately east of the Cascade Range.

The Klamath Basin, in so far as it provides for the inflow to Upper Klamath Lake, may be considered as having an effective area of around 3,500 square miles. Elevations range from 4,150 to nearly 9,000 feet, most of the area lying between 4,200 and 4,600 feet above sea-level. The rim of this basin, roughly 70 miles in diameter, varies from a maximum elevation of around 9,000 feet at Crater Lake on the western edge, to a little under 5,000 feet on the northerly and southerly rims. However, most of the rim is above elevation 5,000 feet. Quite a dense forest of conifers covers the mountain slopes in the western portion of the basin, while the forest is thinner in the eastern part of the area. The mean annual precipitation at established stations varies from around 66 inches in the mountains to 12 inches on the basin-floor. The principal streams flowing into Upper Klamath Lake are Williamson River with its two main tributaries, the Sprague and Sycan, Wood River, and Sevenmile, Cherry, Rock, Crystal, and Fourmile creeks. The region is of volcanic formation, varying from hard lava to pumice and ash which, together with extensive areas of marsh, has a marked effect upon stream-flow. Much of the water-supply is spring-fed to a large degree, the formation acting as an immense sponge, absorbing within itself the valuable waters later to be released throughout the dry portion of the year as a sustained yield.

The Klamath Basin is the principal source of supply of water for the Klamath Irrigation Project of the Bureau of Reclamation and for the power-plants of The California Oregon Power Company located at Klamath Falls and Keno in Oregon and Copco, California. The present hydro-electric development supplied from this source totals 83,785 rated horsepower. A low weir-type concrete dam at the outlet of Upper Klamath Lake operated under Government lease by the Power Company

provides a usable storage of 465,400 acre-feet. Without this dam the approximately 100,000 acres under the Project would, during low-water years, have suffered a deficiency. However, no lack of water-supply has been felt by the Project, because, except for a small prior water-right, its requirements receive first call. It, therefore, particularly behooves the Power Company to exercise every possible precaution to ascertain the probable yield from the basin in order to properly and most efficiently make use of the water available for its use. Here the coordination between plants served from the Klamath Basin source and stream-flow plants on the adjoining Rogue River Area comes into particular play.

During the fall of 1926, in an effort to predict the summer and fall inflow to the lake, the Power Company in cooperation with the Klamath Irrigation Project engineers established snow-stations at strategic locations, in so far as observers were available. We were not in a position to employ the highly developed snow-sampler, now so extensively used, so made use of the single sampling-method whereby a sample is taken in a 3 9/16-inch diameter No. 28 gage galvanized sheet-metal tube, and melted into a 2 17/32-inch diameter receptacle which accentuates the water-depth by two. Comparison with the Mt. Rose long course-sampler shows a good to fair relationship. Naturally, we would have preferred to have had stations at certain more inaccessible locations, but since we were forced to rely on existent observer help, we have utilized such local help consistently, and in most instances have been using the same observers year after year. At the stations where the single-sample method is used, observations are taken and the results sent in on self-addressed cards on the fifteenth and last day of the month. Up to and including 1941, reports were made for the six months, November through April. Since that time we have eliminated the reports for November and April as being of no particular value and not justifying the added expense.

Since 1936, our single-sample stations have been augmented by several long-course stations, three of which duplicate readings at the old single-sample stations. The long-course measurements are made once a month by the Division of Irrigation, Soil Conservation Service, United States Department of Agriculture, with whom we cooperate along with other agencies.

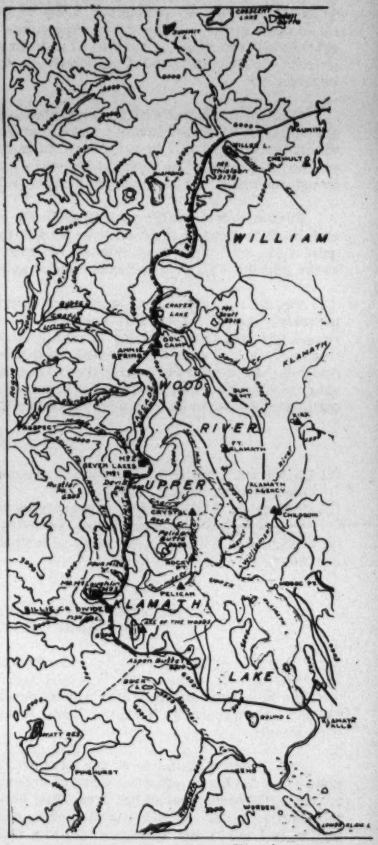
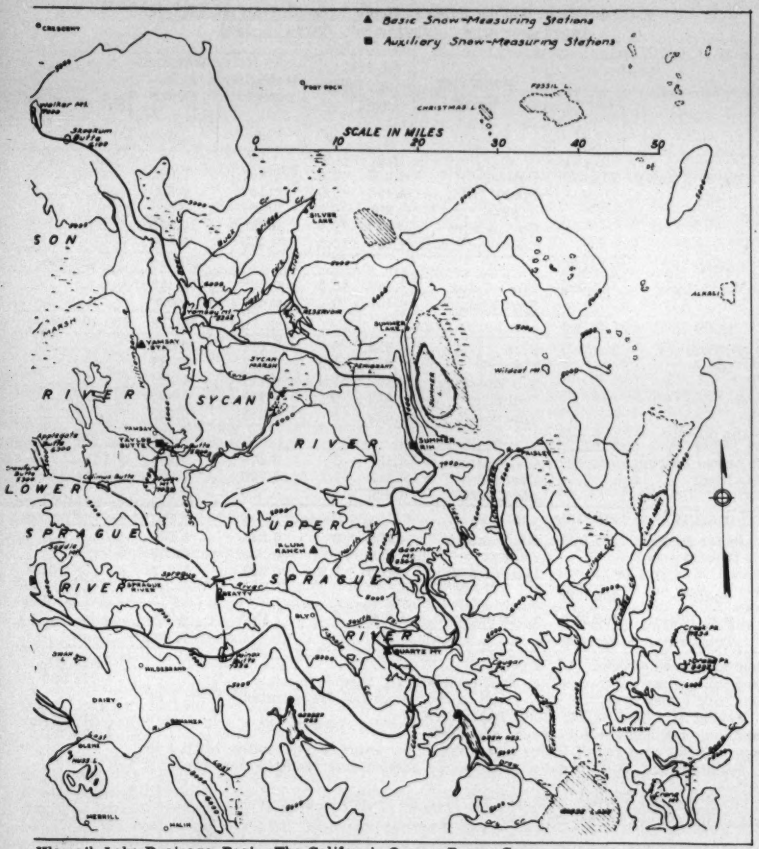


Fig. 1--Upper

The accompanying map (Fig. 1) shows the Klamath Basin divided into six drainage-areas. In arriving at the estimated amount of water in the snow over the entire basin, each sub-basin is figured separately. The reported amount of water in the snow for the several stations within a given area are weighted together on the basis as they individually may be considered representative of a certain proportion of the area in question.

At present the reports from 14 basic stations are used. These comprise mostly the originally established stations, many of them now having 17 years of record. The reports from eight additional stations, more recently established, are not directly used at present, but will be later.

Table 1 gives the basic data used in computing the water in the form of snow over the basin available for conversion into "net inflow" or usable runoff. Paralleling the term runoff we use the expression "net inflow", which is that amount of water available at the outlet of Upper Klamath



Klamath Lake Drainage-Basin, The California Oregon Power Company

Lake for for irrigation- and power-use. It is the net amount left after the several variables such as evaporation and unknown irrigation use up country have had their effect. It is the amount of this net inflow which we endeavor to forecast.

As an example, the method of computing the estimated net inflow for 1942-43, based upon snow-measurements as of March 31, 1943, is shown in Table 1. It might be in order to explain the "multiplier constant" in column (5). This is merely the constant by which the recorded depth of water is multiplied in order to convert it to its proper weighted value as representing this particular station's effect upon the area under consideration. For instance, under III, Williamson River, the mean of the first three stations is assumed to represent average conditions over one-third of the area. Thus each one has a value of $1/3 \times 1/3 = 1/9$ or 0.111. The mean of the last two of the five stations is assumed to represent average conditions over two-thirds of the area. Here each one has a value of $1/2 \times 2/3 = 1/3$ or 0.33⅓.

Table 1--Estimated net inflow of Upper Klamath Lake for 1942-43 based upon snow-measurements March 31, 1943

No.	Sub-basin	Area	Measuring station	Elevation	Water	Multiplier constant	Weighted water-inches [(4) × (5)]	Water-cover [(1) × (6)]/12
		(1)	(2)	(3)	(4)	(5)	(6)	(7)
		acres		feet	inch			acre-feet
I	Upper Klamath Lake	273,000[a]	Pelican	4,200	0.0	0.167	0.000	.....
			Rocky Point	4,150	0.0	0.167	0.000	.....
			Crystal	4,200	4.0	0.167	0.668	.....
			Gov't Camp	6,516	66.6	0.250	16.650	.....
			Lk-O-the Woods	4,960	12.0	0.250	3.000	.....
	Total I	273,000	.....	.....	.....	.....	20.318	462,200
II	Wood River	85,000	Gov't Camp	6,516	66.6	0.333	22.178	.....
			Fort Klamath	4,150	0	0.667	0.00	.....
	Total II	85,000	.....	.....	.....	.....	22.178	157,100
III	Williamson River	812,000	Kirk	4,533	0	0.111	0.000	.....
			Chemult	4,760	15.2	0.111	1.687	.....
			Sun Mountain	5,350	37.6	0.111	4.174	.....
			Chiloquin	4,187	0	0.333	0.000	.....
			Yamsay	4,600	0	0.333	0.000	.....
	Total III	812,000	.....	.....	.....	.....	5.861	396,600
IV	Lower Sprague River	315,000	Chiloquin	4,187	0	0.250	0.00	.....
			Beatty	4,300	0	0.250	0.00	.....
			Klum Ranch	4,800	0	0.500	0.00	.....
	Total IV	315,000	.....	.....	.....	.....	0.00	0
V	Upper Sprague River	325,000	Klum Ranch	4,800	0	0.333	0.000	.....
			Beatty	4,300	0	0.333	0.000	.....
			Quartz Mountain	5,500	5.5	0.333	1.832	.....
	Total V	325,000	.....	.....	.....	.....	1.832	49,600
VI	Sycan River	395,000	Klum Ranch	4,800	0	1.000	0.000	.....
	Total VI	395,000	.....	.....	.....	.....	0.000	0

Grand total area [column (1)], acres	2,205,000
Grand total gross water-cover on hand [column (7)], acre-feet	1,065,500
Grand total gross water-cover to come, based on normal precipitation[b] April 1 to August 31 = (3.36 in/12) (2,205,000), acre-feet	617,400
Grand total estimated water-cover, acre-feet	1,682,900
Assume 40 per cent runoff-factor (see Table 2) for estimated net inflow April 1 to September 30, 1943, namely, gross water-cover times runoff-factor, acre-feet	673,200
Net inflow October 1, 1942, to March 31, 1943, as recorded, acre-feet	900,400
Total estimated net inflow, acre-feet	1,573,600
or say	1,575,000

[a]Area of surface of Lake not included. [b]Precipitation at Chiloquin, Oregon.

Then the Gross Water Cover as of March 31 is obtained. To this is added the water available from precipitation still to come. This is taken as a constant amount of 617,400 acre-feet, arbitrarily assuming that the normal precipitation at Chiloquin for the five months, April through August, of 3.36 inches, represents the average rainfall over the entire Klamath Basin. We then obtain the "Total estimated gross water-cover", which must be corrected by the several unknown variables among which are up-basin irrigation, evaporation, effect of previous years, soil-moisture content, etc. Previous years' inflow, particularly the sustained effect of a series of above-normal, normal, or below-normal years, has a marked effect upon the net results of the year in question. This correction is made by applying the proper runoff-factor, which is the final step in arriving at the estimated net inflow.

As can readily be seen, choosing the proper runoff-factor is really what decides whether a reasonable estimate is to be made. However, if a good basis is established for choosing the proper factor, then other assumptions such as area involved and the effect of a certain station on a repre-

Table 2--Estimated net inflow, Upper Klamath Lake, data used for choosing runoff-factor

Year	Total water in snow on watershed March 31, acre-feet	Precipitation at Chiloquin, per cent of normal			Runoff-factor, per cent		Net inflow, Upper Klamath Lake, acre-feet				
		Year	Sep.-March	April-August	Computed on basis of actual inflow and precip.	Used in estimate	Actual Oct.-March	Actual April-Sep.	Estimated April-Sep.	Actual total	Estimated total
1924-25	.....	126.7	111.7	182.0	.....	.....	726,300	514,500	.....	1,240,800	.....
1925-26	.....	64.1	61.1	76.0	.....	.....	546,900	240,500	.....	787,400	.....
1926-27	718,500	109.6	116.0	83.3	49.5	45.0	787,500	609,800	600,500	1,397,300	1,389,000
1927-28	530,500	80.2	78.8	85.1	43.0	40.0	721,500	454,300	458,500	1,175,800	1,180,000
1928-29	414,500	54.5	50.2	71.1	36.0	30.0	548,400	305,700	308,600	854,100	857,000
1929-30	252,500	75.3	83.7	42.2	45.8	30.0	584,200	234,700	260,800	818,900	845,000
1930-31	285,500	57.8	58.7	53.5	28.8	20.0	457,600	177,200	180,400	634,800	638,000
1931-32	685,500	102.3	86.4	164.0	18.1	20.0	499,100	293,200	260,900	792,300	760,000
1932-33	1,184,000	72.6	72.5	72.9	19.2	18.0	456,400	313,700	323,600	770,100	780,000
1933-34	155,000	71.7	68.2	85.1	29.1	25.0	478,800	198,200	193,200	677,000	672,000
1934-35	880,000	94.0	90.4	108.3	24.5	25.0	489,200	385,300	373,800	874,500	863,000
1935-36	1,134,500	100.0	96.5	114.4	23.4	25.0	577,500	430,300	437,600	1,007,800	1,015,000
1936-37	947,700	102.8	64.7	252.0	14.4	25.0	492,100	359,700	390,900	851,800	883,000
1937-38	1,528,400	125.8	145.2	48.2	41.1	35.0	719,000	752,800	751,000	1,471,800	1,470,000
1938-39	581,300	72.2	77.6	50.6	34.6	25.0	564,200	309,400	298,800	873,600	863,000
1939-40	617,000	134.2	151.5	61.0	43.4	35.0	678,400	431,100	431,500	1,109,500	1,110,000
1940-41	569,000	115.3	101.8	167.6	24.9	33.0	577,800	372,800	391,200	950,600	969,000
1941-42	607,500	112.5	106.6	134.6	31.5	35.0	640,900	452,700	428,200	1,093,600	1,069,000
1942-43	1,067,000	.....	152.0	.....	.....	40.0	900,400	.....	674,600	.....	1,575,000

sentative area is not so important just as long as one consistently makes the same assumptions.

Table 2 gives the essential data used in choosing the runoff-factor. The longer the record, the better one should be able to pick out the proper factor. The Table shows by years the kind of seasons formerly attained. The season to come is very greatly affected by what has gone before. This may not be so true where the snow-cover is on a relatively impervious area, in which case the runoff can generally be estimated as a direct relation to the snow-cover. However, a formation such as makes up the Klamath Basin in effect really provides a large underground storage-reservoir, which is very much affected by performances of previous seasons and years.

So we utilize the records of precipitation at Chiloquin, which has an annual mean of 16.60 inches, and note particularly the present performance-period September through March with respect to that of the previous period April through August.

In the example worked out in Table 1, estimating the net inflow for 1943 based upon measurements of March 31, 1943, we have chosen a 40 per cent runoff-factor, noting from Table 2 that the precipitation (September to March) is 152 per cent of normal and that it follows a last summer's (April to August) precipitation of 135 per cent of normal. This is after the pattern of 1937-38 when a 35 per cent factor was used. However, for the last few years the net inflow has been increasing due to the continued replenishment of the underground storage, last year being considered good. So we feel justified in raising the 1938 and last year's runoff-factor figure to 40 per cent and predicting a total 1942-43 net inflow of 1,575,000 acre-feet. The six-month forecast is then broken down into monthly forecasts on the basis of existing snow-conditions and trends in previous years. Of course, all forecasts are predicated upon normal conditions of weather during the period of runoff.

We have found no consistent yearly relation between water in the form of snow on the ground and runoff due, we believe, to the character of formation under the cover. We have tried combining the results of present and previous years' precipitation and inflow-figures, with the hope of finding that elusive constant which may be applied directly to the "Estimated gross water-cover" to date and thus give us the answer of what is to come, and we are still at it. For the present we rely upon a method which might be considered more practical than theoretical in that the matter of personal judgment enters somewhat largely into the picture. We do feel that we get rather fair results, and that the benefits derived from the forecasts fully justify the efforts expended.

Addendum relative to runoff-factor

In connection with the foregoing paper it might be advisable to further discuss the "Runoff-factor" shown in Table 2.

The one used in actually estimating the net inflow is greatly dependent upon the judgment of the forecaster. The chosen factor is applied to the summation of the acre-feet of water in the form of snow on the ground as of March 31 and a constant 617,400 acre-feet, the latter figure being the normal precipitation at Chiloquin, Oregon, from April 1 to August 1, applied to the total area.

The computed runoff-factor shown in Table 2 is obtained after the season's operation by working backwards from actual precipitation and net-inflow figures, and is mainly of interest as a matter of comparison and trend.

Since determination of a runoff-constant is one of the principal factors involved in accurate forecasting of the probable inflow to the Upper Klamath Lake, the question arises as to the principal causes of this variation and whether or not ways may be found of reducing the unknown factors.

We know by observation that dry, wet, or frozen ground at the time of the first winter snow-cover has an important effect upon the total runoff, as well as the rate thereof, but to what extent is not known.

A start has been made in this particular basin by taking measurements of soil-moisture content at Annie Spring, Chemult, and Quartz Mountain, and if these records are continued and other stations established so as to obtain a good representative coverage of the area, they may, in time, prove of some value.

Another possibility would be the establishment of ground-water-level records, taken from wells or springs unaffected by surface-water.

Such records might or might not be of benefit to the forecaster, but the importance of accurate forecasting of runoff and resultant inflow to the storage-reservoir for irrigation and power-generation as well as river-control are of unquestioned benefit.

The California Oregon Power Company,
Klamath Falls, Oregon

DISCUSSION

J. E. CHURCH (University of Nevada Experiment Station, Reno, Nevada)--We have had a similar experience with the Humboldt River, Nevada, that is apparently one of the most erratic streams in its relation to snow-cover that has so far come to our notice. We have just found that the water-table has a basic and close relationship to the present excess runoff that is occurring from that stream. We have found that by using the snow-cover as base-datum and modifying this by the influence of the water-table we come close to the total of runoff. This has now occurred for two years while the water-table has been steadily approaching its maximum height.

Therefore, if the Klamath River is considered as a combination of accumulating ground-water with additional seasonal snow and rain, the joint influence should closely express the final discharge. Fortunately the lava-fields steady the flow of both the Pitt and the Klamath as well as produce a carry-over from one season to the next.

A similar study has now been well started in the Charleston Mountain in southern Nevada to seek a method of forecasting the fluctuation of the artesian wells in the valleys at its base. It may take several seasons before the relationship between snow and fluctuation in artesian flow becomes apparent.

BERTRAM S. BARNES (Regional Engineer, United States Weather Bureau, San Francisco, California)--I have been wondering how the water equivalent would compare with the soil-moisture capacity. We are dealing with a case where the major loss, in the long run, must be evaporation, because it seems to me that the water that goes into ground-water storage would practically all drain out in six months.

If you had a 66-inch water-equivalent over the snow-covered area, it is unlikely that the soil would take and hold a very heavy percentage of it.

If the difference between the highest runoff-factor and lowest--which are 49 and 18--were 31 per cent, and the factors were based on the soil-moisture deficiency, that would mean an exceedingly great water-capacity for the soil.

How long do you think there would be an appreciate carry-over of ground-water storage?

R. A. WORK (Irrigation Engineer, Soil Conservation Service, Medford, Oregon)--Referring to Mr. PEDERSON'S question as to how the runoff-factor could be off and still give the correct result, there must be a compensating factor. The fact that the basin is divided into six subsidiary drainages, in each of which acre-feet have been computed, might account for a part of it. There has to be a compensation. In some years, deviations of precipitation from normal after date of forecast accounted for the compensation. Anyway, the proof of the pudding seems to be in the eating. The estimates are phenomenal.

As regards the query by Mr. BARNES on magnitudes of water-equivalent, they are given just for one year--the current year, April 1, 1943--as 0, 0, 4.0, 66.6, 12.0, 15.2, 37.6, 5.5, and all the rest 0. It so happens that one or two of these stations, in a year like this when there was no low snow, carried much of the load of this entire computation.

Regarding Mr. Barnes' comment that the great difference between runoff-factor would indicate an exceedingly great water-capacity for that soil, it may be noted that the area is a great one of underground grottos, fissures, etc., which may take several years to fill. The lava-formation is like a great sponge. It would take several years during a period of deficient precipitation to draw off the reserve supply. In other words, there is a great equalizing basin under there.

Answering Mr. Barnes as to how long there would be a carry-over, I would say, as a quick estimate, approximately three years.

HARRY OLSEN (communicated July 16, 1943)--As indicated by Dr. CHURCH, the runoff of the previous season or series of seasons does have a considerable weight in choosing the runoff-factor used. His tabulation of "Monthly percentages of normal runoff in varying types of watersheds", very nicely illustrates the hold-over characteristics of the lava or volcanic formation such as is present in the Klamath Basin.

Table 1--Monthly percentage of normal runoff in varying types of watersheds

Month	Alluvial soil, Humboldt, Palisade (Nevada)	Granite soil, Upper Kern, Kernville	Lava soil		
			Klamath, Spencer Bridge	Upper Klamath Lake, Klamath Falls	North Fork, Route River, Station 722, Prospect
Oct.	1.7	3.3	5.0	6.3	4.8
Nov.	2.2	2.8	6.0	8.0	6.6
Dec.	1.9	2.8	7.8	10.0	8.0
Jan.	2.6	3.9	9.1	10.1	8.2
Feb.	3.8	3.6	9.4	9.9	9.1
Mar.	12.0	6.1	11.9	13.2	10.3
Apr.	19.0	10.1	13.3	13.1	13.0
May	20.0	17.3	12.4	10.6	14.2
June	23.5	22.4	9.5	6.0	10.8
July	8.7	11.6	6.8	3.8	5.9
Aug.	1.5	5.3	4.6	4.0	4.6
Sep.	0.8	3.1	4.1	5.0	4.5
Totals	97.7[a]	92.3[a]	99.9[a]	100.0	100.0
Mar.-July	83.2	67.5	53.9	46.7	54.2
Apr.-July	71.2	61.4	42.0	33.5	43.9

[a]Note by Dr. Church: The failure of the monthly percentages in my tabulations to add to the exact total of 100 per cent is probably due to occasional gaps in the data; in any case the percentages are sufficiently close to present the picture.

Dr. Church used the record of the Klamath Basin at Spencer Bridge in his tabulation. Due to the fact that the Klamath Project diverts through their "A" canal, around 200,000 acre-feet during the period April to September above the Spencer Bridge Station and since there may be either inflow into or diversion from Klamath River through the Lost River Diversion (also in connection with the Project) which is also above the Spencer Bridge Station, a truer picture would be obtained by using the "net inflow" into Upper Klamath Lake. This "net inflow" is the amount of water available at the outlet of the lake after the variables such as evaporation and unknown irrigation-use from streams and springs flowing into the lake have had their effect.

To Dr. Church's table has been added the percentage-figures based upon the net-inflow records of Upper Klamath Lake, using the 38-year mean (1904-42). It will be noted that his findings and conclusions relative to soil-effect are still further verified by using the above, there being a still greater spread during March to July and April to July. The fact that July shows the minimum flow instead of September is probably due to irrigation up-country above the Lake outlet.

To Table 1 also has been added the figures based upon the record of Station 722, North Fork of Rogue River, the source of which adjoins the Klamath Basin on the west in the Crater Lake Region and which is also in a volcanic formation watershed. By coincidence the results rather closely follow Dr. Church's percentages using the Klamath River, Spencer Bridge Station.

A SIMPLE PROCEDURE FOR THE DAY-TO-DAY FORECASTING OF RUNOFF FROM SNOW-MELT

Ray K. Linsley, Jr.

Synopsis--During recent years numerous methods for the prediction of rate of snow-melt and resultant runoff have been presented [see 1, 2, 3, 4 of "References" at end of paper]. Some solutions were based on thermodynamic principles. Others made use of simple empiricisms. As yet, however, no procedure has completely supplanted the use of the degree-day factor [4, 5]. The outstanding virtue of the degree-day method is its extreme simplicity. Only records of dry-bulb temperature are necessary to compute degree-days and a simple multiplication by a degree-day "factor" completes the computation of the volume of snow-melt. The great disadvantage of the procedure is that it neglects humidity, radiation, and other factors known to influence the melting-rates of snow. It is the purpose of this paper to outline the methods developed by the office of the Weather Bureau at Sacramento, California, for applying the degree-day procedure to river-forecasting in the Sacramento and San Joaquin river-basins.

Introduction--In the development of river-forecasting schemes for the Sacramento River District it was necessary to include a procedure which would enable the forecaster to anticipate the probable contribution of melting snow to stream-flow, especially during flood-periods. Since melting snow is not ordinarily a large contributor to floods in this region [6] and since the forecast for the entire district, comprising some 45,000 square miles, must be completed in a very short time, the procedure for predicting snow-melt runoff had to be as simple and as mechanical as was consistent with the necessary accuracy. Few records of meteorological elements other than temperature and precipitation are available from the remote areas of the Sierra Nevada where the heavy snowpack accumulates. These facts all indicated that the degree-day procedure would probably be the only satisfactory approach.

There are two difficulties which must be overcome before such a procedure can be considered adequate for purposes of forecasting. The first of these arises from the extreme range in elevation between the lower limit of the snow and the upper elevation of the basins. Because of this difference in elevation melting may often take place over only the lower portion of the snow-field. The second difficulty develops because the degree-day number is only an approximate index of many melting-factors. It therefore is quite likely to be a variable, and the laws governing this variation must be understood before the procedure can be applied.

The solution finally adopted is based on the use of two curves. The first has been named the "unit-melt diagram" (Fig. 1) while the second is the degree-day-number curve (Fig. 2).

The unit-melt diagram--Depending upon antecedent conditions, the lower limit of the snowpack in the Sierra Nevada may range from about the 3,000-foot level upwards. Melting of snow can take place only in the zone from the snow-line up to approximately the elevation of the 32° isotherm. Runoff from the melting snow will probably only occur in the lower portion of this melting-zone, since in the upper reaches most of the available heat will serve only to ripen the snow to the point where subsequent melting can result in runoff.

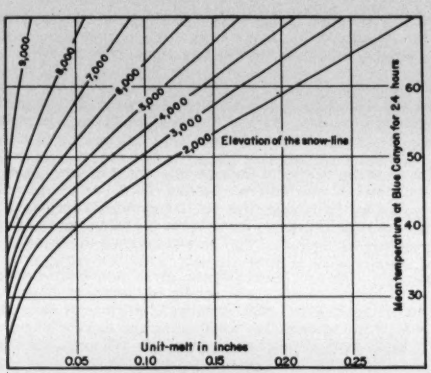


Fig. 1--Unit-melt curves, Tuolumne River above Don Pedro Dam

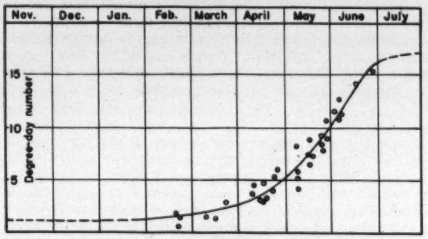


Fig. 2--Degree-day-number curve, Lower San Joaquin Basin

In applying the degree-day method to estimate the snow-melt or runoff from this zone it is first necessary to determine the average number of degree-days above 32° F which occurred over this melting-zone during a given period. The computation involves the steps of:

(1) Dividing the basin into intervals of elevation
(2) Determining the mean temperature in each elevation interval and converting this temperature to degree-days above 32° F
(3) Weighting the degree-days in each zone in proportion to the drainage-area within each zone
(4) Dividing the sum of the weighted degree-days by the total basin-area to get average degree-days for the basin

The unit-melt diagram of Figure 1 was computed in just this manner and thus permits the forecaster to determine the average number of degree-days effective for snow-melt at a single entry. The controlling elements are the temperature at an index-station and the elevation of the snow-line. The final result is given in terms of "unit-melt" rather than degree-days. The term unit-melt as used in this paper may be defined as the depth of runoff in inches over the entire drainage-basin if 0.01 inch of runoff occurs in the melting-zone for each degree-day above 32° F. It is determined simply by dividing average degree-days over the basin by 100.

Figure 1 makes use of only one temperature index-station. Temperatures at other elevations were determined by assuming a lapse-rate of temperature of 3° F per 1000-foot change in elevation. This approach was necessitated by the lack of available stations. More stations would have been used had they been available. The assumption of the lapse-rate of 3° F per 1000 feet is justified by the fact that this diagram is designed for use primarily during flood-periods when heavy rain would make the moist adiabatic lapse-rate applicable. If desired, similar curves could be developed

assuming other values of lapse-rate. A lapse-rate of 3°5 F per thousand feet proved more satisfactory in the Upper San Joaquin Basin. In any case if the index-station is selected near the average elevation of the snowpack, errors in the assumed lapse-rate will be at least partially self-compensating.

Since degree-days are a function of both time and temperature, the unit-melt diagram must be developed for a specified time-unit. Figure 1 applies for 24-hour periods. A similar diagram could be developed for use with six-hour periods or values from Figure 1 could be divided by four.

The relative positions of the curves of the unit-melt diagram are dependent on the percentage of basin-area within each interval of elevation. Basins of similar topographic characteristics, therefore, will have, regardless of size, nearly similar unit-melt diagrams. It has been found possible to use the same unit-melt diagram for several basins without serious error. A comparison of curves of percentage-area against elevation will indicate the feasibility of this step.

The degree-day number--The unit-melt diagram gives values of snow-melt runoff only if one degree-day results in 0.01 inch of runoff. It is usually necessary to determine a factor by which the unit-melt may be multiplied to give actual volumes of snow-melt or runoff. Since relations of this sort are used primarily for stream-flow forecasting and since it is quite difficult to determine actual volumes of snow-melt, the degree-day number will usually express the runoff per degree-day.

The degree-day number may be determined by dividing the total runoff from the basin for a short period by the concurrent unit-melt. The observed runoff should be corrected for runoff from rainfall. This may be done by means of a rainfall-runoff relation for the basin, but because of the possible error in such a procedure it is usually best to determine the degree-day number from periods when little or no rain occurred. Correction of the observed runoff for base-flow will undoubtedly improve the results. However, the separation of base-flow from surface-runoff during periods of snow-melt is a rather difficult process and little error will result if the base-flow is included.

Runoff from snow-melt probably reaches the stream mostly through sub-surface and ground-water channels with relatively small amounts of true surface-runoff. If we consider three successive weekly periods, some of the accretion to base-flow during the first week will appear as stream-flow during the second week, making the apparent degree-day number computed for the second week too high. However, some of the accretion to base-flow during the second week will appear in the streams at a later time, thus compensating for the first error. If the degree-day number is computed for successive periods during the melting-season, it is probable that if one computation gives a figure that is too high the following period may give a result that is too low. Thus the average throughout the season should be approximately correct.

If the degree-day number determined in the manner just discussed appears to be a constant or reasonably constant value, the solution is complete. In fact, the abscissas of the unit-melt diagram may then be multiplied by this constant and the use of a separate degree-day factor eliminated.

It is characteristic of basins tributary to the Central Valley of California that the degree-day number increases as the season progresses. Figure 2 is a curve showing the variation of the degree-day number with calendar date as determined for the Stanislaus and Tuolumne rivers. Almost identical curves were developed for the Mokelumne, American, Kings, Kaweah, Merced, and Upper San Joaquin rivers, but the variation becomes less pronounced in the northern basins.

It is believed that the principal cause of this variation is the gradual ripening of the snow as the season advances, allowing greater amounts of runoff for the same amount of melt or same number of degree-days. The curve also reflects a normal seasonal variation in humidity, solar radiation, and other melting factors for which the dry-bulb temperature alone is not a completely adequate index. It is possible, since the elevation of the melting-zone increases as the season progresses, that the curve also reflects some errors in the area-elevation relationship used to develop the unit-melt curves. The temperature index-station, Blue Canyon, is situated well to the north of the Stanislaus and Tuolumne rivers. The seasonal range in temperature is greater in the southern portion of the valley. Thus during May and June the temperatures at Blue Canyon may be lower than the temperatures at the same elevation in the basins. This is substantiated by the fact that the curves for the northern basins for which Blue Canyon is used as an index are lower during May to July.

The points plotted on Figure 2 represent data taken from the Tuolumne River above Hetch Hetchy, Don Pedro, and the Stanislaus River above Melones. The scatter of points about the average curve undoubtedly results from short-term variations in meteorological conditions, errors in separating runoff from base-flow, errors in estimating elevation of the snow-line, and errors in basic data. When the curve is applied to actual forecasting, much of this deviation can be eliminated. It has, for example, been the writer's experience that it is much simpler to estimate the current elevation of the snow-line than it is to estimate its position on a given date several years past. Moreover, the forecaster can superimpose on the average degree-day-number curve, a secondary variation to allow for known variations in humidity, radiation, and other elements from the average conditions.

Snow-melt by rainfall--The water-content of snow melted by rainfall on the snow-surface is readily susceptible to computation by the procedures just outlined. The heat of fusion of ice is 144 British thermal units per pound while the specific heat of water is one British thermal unit per pound. If the snow is initially at 32° F, then the depth of water melted from the snow by heat from rain is [2]

$$D = (1/144)\, P(T - 32) = 0.007\, P(T - 32) \qquad (1)$$

where P is the depth of rainfall in inches and T is the temperature of the rain. T is best expressed by the wet-bulb temperature during the rain. During periods of rainfall the wet-bulb and dry-bulb temperatures are very nearly equal. The value of unit-melt taken from a diagram similar to Figure 1 therefore gives the term 0.01 (T - 32). Then

$$D = 0.7\, P\, M_u \qquad (2)$$

where M_u is the unit-melt.

It has been noted by many writers [2, 6, 8] that the quantity of water melted from snow by rainfall is small in comparison with other factors. This is quite true but in flood-forecasting it may not be negligible. For example, assuming a snow-line of 5,000 feet and mean temperature of 45°, the unit-melt from Figure 1 is about 0.04 inch. Assuming six inches of rain in 24 hours (not an infrequent occurrence), the resulting snow-melt from equation (2) would equal 0.17 inch on the entire basin. For the American River at Folsom, California, this might increase the crest from 0.5 to 1.0 foot.

Distribution of runoff--The distribution of the predicted runoff from snow-melt with respect to time may be accomplished in various ways. In the Sacramento River District, snow-melt occurring without appreciable rainfall is distributed by means of distribution-graphs. These graphs were developed by trial from records of stream-flow for periods of snow-melt without concurrent rainfall. They are much less sharply peaked than are the distribution-graphs for rainfall-runoff.

When runoff is primarily from rainfall, the estimated snow-melt runoff is added to the predicted rainfall-runoff and the total used in predicting stream-flow by the usual forecast-methods, unit-graphs, or rainfall-runoff-crest-stage relations. In some basins within the district no records of stream-flow are available for Weather Bureau river-gages. In such cases the flood-crest is usually predicted directly from rainfall without recourse to runoff. The degree-day-number curves for these basins are derived from records for adjacent basins and the values of degree-day number are doubled. The predicted snow-melt by this means is added to the rainfall. This is equivalent to assuming a rainfall-runoff percentage of 50.

In the upper San Joaquin Basin where prolonged heavy snow-melt runoff occurs the distribution-graph procedure does not prove satisfactory for predicting the outflow-hydrograph, and a routing procedure was developed.

A recession-curve for periods of snow-melt runoff was developed by plotting flow on one day against flow 24 hours later [9] (Fig. 3). This recession is quite similar to the ground-water recession but does not adhere to the equation $Q = Q_o k^t$ developed by Barnes [8], probably because of the inclusion of small amounts of surface-runoff at high flows. From this recession a curve of storage versus flow was developed. The storage equation is

$$(\bar{I} - \bar{O}) = \text{change in storage} \qquad (3)$$

where $\bar{I}$ and $\bar{O}$ equal average inflow and outflow, respectively, for the routing period. This can be altered to read

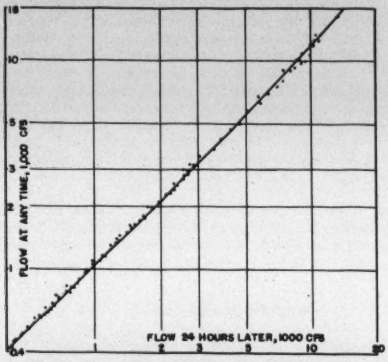


Fig. 3--Recession, Kings River at Piedra

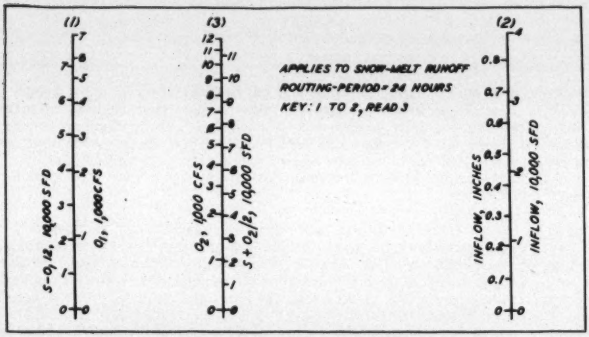


Fig. 4--Routing nomogram, Kings River at Piedra

$$\bar{I} - (1/2)\,(0_1 + 0_2) = (S_2 - S_1) \qquad (4)$$

where the subscripts 1 and 2 refer to the beginning and end of the period, respectively, and S is the storage. Rewriting equation (4)

$$[I + (S_1 - 0_1/2)] = (S_2 + 0_2/2) \qquad (5)$$

This is susceptible to a nomographic solution (Fig. 4). Moreover, since storage is a function of outflow, $(S + 0/2)$ is also a function of 0. Values of 0_1 and 0_2 may therefore be inserted in place of $(S_1 - 0_1/2)$ and $(S_2 + 0_2/2)$ on the nomogram. Since the inflow from melting snow is computed in inches, values of $\bar{I}$ in inches can be inserted in place of the values in second-foot-days on scale (3). A straight-edge held from the proper flow-value for the beginning of the routing period to the estimated value of I for the period permits reading 0_2 from the central scale.

This provides a very rapid forecasting-procedure and by reversing the process can be used to compute daily values of inflow for the development of the degree-day-number curve.

Conclusion--A method has been presented for the day-to-day prediction of runoff from melting snow with a minimum of labor. The usefulness of the method is increased by the fact that the work-

ing curves used in the method may often serve more than one basin. The procedure is applicable in those regions where a semi-permanent snowpack develops during the winter and is particularly adaptable to the basins in which an extreme range in elevation restricts melting at any instant to limited portion of the snow-cover. No new theoretical approach to the problem of melting snow has been introduced, but it is believed that the method should provide a simple and practical tool for hydrologists.

A more complete system of observations of snow-line elevation is essential before the full value of this procedure can be realized in many basins. It is believed also that systematic observations of quality of snow will provide valuable information on the degree-day number. It seems probable that this number may actually prove nearly constant when adjustment for snow-quality is included.

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DISCUSSION

R. A. WORK (Irrigation Engineer, United States Division of Irrigation and Oregon Experiment Station, Medford, Oregon)--I was interested in Mr. LINSLEY'S hope that the day-degree snow-melt would be a constant. CLYDE appeared to find that snow-melt was a constant. In fact, in Clyde's bulletin "Snow melt characteristics," he gives the value. But Messrs. CHILDRETH and FROST and I, working at Crater Lake, found that snow-melt there was not a constant.

The questions of snow-quality, snow-texture, and day-degree versus hour-degree entered into the picture. Our observations of snow-melt were refined to the point of calculation of hour-degrees, and there seems quite a difference in behavior of snow under varying conditions of hour-degrees above 32 compared to day-degrees above 32.

THREE UNUSUAL RUNOFF-YEARS IN THE HUMBOLDT BASIN, NEVADA, 1940-41, 1941-42, AND 1942-43

J. E. Church and H. P. Boardman

The presentation of the paper "The Humboldt Basin, Nevada: Two unusual years, 1940-41 and 1941-42" at the Pasadena Regional Meeting [Trans. Amer. Geophys. Union, pp. 156-159, 1942] and "Forecasting runoff for power and irrigation from relatively low-level areas" by HARRY OLSEN and E. B. PRICE at the Corvallis Regional Meeting (pp. 55-62) makes the present paper desirable as emphasizing the factors of soil-moisture and ground-water level that have previously seemed quite subordinate to those of snow-cover and precipitation.

Unusual opportunity for observing the effect of high water-table on increasing the flow of the Humboldt has been afforded for a second year, while abnormal snow-melt, winter rains, and

above-normal summer rains are accumulating data of future use in foreseeing abnormalities in the seasonal flow.

Although in the Sierra Nevada the runoff usually corresponds closely with the water-content of the snow-cover, other factors than the snow-cover, materially affect the flow of the Humboldt. For example, in 1940-41 double normal precipitation throughout April to June, when most effective on the snow, produced an excess of 121,500 acre-feet or 48.6 per cent of normal above the 150,000 acre-feet forecasted.

In the water-year of 1941-42 the building up of a high water-table by double normal rains in 1941 that continued into the winter and the sudden melting of low-level snow accumulated during the winter increased the flow of March to July of 1942 from 193,280 acre-feet indicated by the snow-cover to 493,860 acre-feet, or an excess of 139.8 per cent of normal.

The extremely high water-table of the present season of 1942-43 has already raised the stream-flow (June 12) to 168 per cent of the normal for March to July although the snow-cover on March 1 was only 91.4 per cent of its normal. The effect of the excessive winter precipitation of 137.6 per cent, of which 46 per cent of normal was rain or melting snow, is still uncertain.

Table 1--Tabular comparison, runoff in Humboldt Basin, 1940-43

Year	Snow-cover (per cent of March 1 normal)	Actual runoff (per cent of March to July)	Divergence (per cent of normal)
1940-41	71.4	106.2	34.8
1941-42	89.8	229.7	139.9
1942-43	91.4	168.0 to June 12	76.6 to June 12

Effect of spring-flood and high water-table--To obtain a closer comparison, recourse has been had to the monthly percentage of the flow for April to July for 1942 alone. Stations representing high-level as well as low-level runoff have been selected to isolate so far as possible the effect of the spring-flood of April. The resulting Table 2 seems definite.

Table 2--Monthly percentage of total flow, April to July

1942	April	May	June	July	April to July	
	pct	pct	pct	pct	pct	acre-feet
Marys River at Cabin Field (low level)	47	30	20	3[a]	100	58,000±
Lamoille Creek at Power House (high level)	7	19	53	21	100	33,740
Lamoille Creek at McIntyres (low level)	24	24	36	16	100	53,620
South Fork at Boltons (high level)	10	23	50	17	100	63,570
South Fork at Bullion (low level)	27	28	35	10	100	139,970
Humboldt River at Palisade (low level)	36	25	30	9	100	431,340
Humboldt River at Palisade (normal low level)	26	30	33	11	100	182,400
Little Humboldt Basin at Martin Creek (low level)	39	34	23	4	100	19,880

[a]Estimated.

On Lamoille Creek and South Fork the relative April flood-flow was three times greater below the 6,000-foot altitude than above and apparently even more on the Marys River and in Little Humboldt Basin.

The isolation of the two factors of flood-melting and high water-table is made easy by the natural fluctuation of the former and the steadiness of the latter. For example, in the comparison in Table 3 of the runoff of the Humboldt at Palisade for 1942 and its normal, with the single exception of April when the flood occurred, close uniformity between seasonal runoff and normal prevails throughout the season despite the quantitative difference between them.

Table 3--Comparison of 1942 and normal runoff of Humboldt

Item	March	April	May	June	July	Total	
	pct	pct	pct	pct	pct	pct	acre-feet
Humboldt, 1942	13	32	22	26	7	100	493,860
Humboldt, normal	15	22	26	28	9	100	215,000

Table 4, by H. P. Boardman, shows the close harmony of the four months March, May, June, and July, as well as the great difference in per cent of normal for April.

Table 4--Comparison of March, May, June, and July with April

Month	Normals		Actual 1942		
	Acre-feet	Pct	Pct	Acre-feet	Per cent normal
March	32,600	19	19	62,500	192
May	54,500	33	32	107,700	197
June	60,400	36	38	128,400	213
July	20,300	12	11	37,140	183
Totals	167,800	100	100	335,740	200
April	47,200	....	....	158,100	335

The quantitative flood-effect is therefore the ten per cent divergence in April or, on the basis of the total flow of 1942 of 493,860 acre-feet, 49,386 acre-feet. This harmonizes with excess accumulation of 50,000 acre-feet during March, 1913-14, due apparently to high temperature (2°0 F above normal).

The water-table effect on the basis of the excess above 90 per cent of normal represented by the snow and corrected for flood in April is as follows in acre-feet: March, 33,180; April, 66,234; May, 58,650; June, 74,040; July, 18,870; and total, 250,974.

The gain apportioned to the two factors is thus (1) spring-flood 50,000 acre-feet and (2) high-water table 250,000 acre-feet. In view of the area of probably 6,000,000 acres contributing to the stream-flow of the upper Humboldt, this excess of 250,000 acre-feet would be only one-half inch if spread over the entire area.

The factor of temperature, other than in April, was dormant or regressive as shown by the monthly temperature-departure at Elko and Lamoille in Table 5.

Table 5--Temperature-departure from normal

Station	March	April	May	June	July
	°F	°F	°F	°F	°F
Elko	-4.6	-1.7[a]	-5.8	-5.1	+0.9
Lamoille	-3.4	-0.9[a]	-3.1	-2.3	+2.6

[a]In early April the temperature as measured at Lamoille suddenly rose to 12°0 F above normal and continued at +6°0 F during the following two weeks, causing a runoff at Palisade for the month of 152,000 acre-feet; the temperature-departure at Elko during the first three weeks was +3°0 F and fell to -1°5 F for the month.

Precipitation was likewise without effect, being in moderate excess in April and May but deficient in March, June, and July. Thus the excess and deficiency were approximately in balance.

Table 6--Precipitation-departure from normal

Basin and station	March	April	May	June	July
	inch	inch	inch	inch	inch
Upper Humboldt					
Tuscarora	-1.37	+0.26	+0.02	-0.53	-0.53
Arthur	-1.06	-0.84	-0.12	-0.65	-0.73
Lamoille	-0.60	+0.82	+1.44	-0.52	-0.14
Hylton	-1.44	+0.80	+0.64	-0.58	-0.58
Little Humboldt					
Paradise Valley	-0.53	+0.34	-0.07	-0.19	-0.33
Orovada	-0.55	+0.64	+1.59	+0.46	-0.18

Forecast for 1943--The radio forecast for the upper Humboldt made April 10 still holds except that the maximum runoff may be considerably above 150 per cent of normal. This forecast was as follows: Precipitation, November to February, 137.6 per cent of normal; snow-cover, March 1, 91.4 per cent of normal (but at low levels only 42.2 per cent of normal); water-table highest of record; runoff at Palisade will be fully 150 per cent of new normal of 215,000 acre-feet for March to July. (The final forecast based on complete data was 185 per cent.)

Since the high water-table affects the broad alluvial basins rather than the mountain canyons, this maximum must be applied mainly to the Humboldt at Palisade and the valley areas of the tributaries.

In the lower Humboldt, conditions have varied from high floods, heavy snow-cover, and excessive precipitation in the Little Humboldt-Quinn River Area on the north to normal precipitation in the Reese River Area on the south. The reservoirs at the foot of the Humboldt have been overfilled and are being drawn-down for safety.

Table 7--Forecast summary

Basin	Snow-cover March 1, per cent of normal and mean		Percentage effect of water-table (basis 1942)	Normal runoff March to July, acre-feet	Probable flow		Possible maximum flow	
					Per cent normal	Acre-feet	Per cent normal	Acre-feet
Humboldt River at Palisade	High level 91.4 Low level 42.2	66.8	116.0	215,000 (new)	185	397,750	200	430,000
Northern feeders	High level 104.9 Low level 57.5	73.3	116.0	.....	189	.....	200	.....
Lamoille Creek at Power House	97.9		116.0	22,800 (old)	214	48,800	214	48,800
South Fork at Boltons	70.1		116.0	35,000 (old)	186	65,100	186	65,100
Martin Creek near Paradise	122.1		.....	20,320 (new)	125	25,400	175	35,600
Quinn River	122.1		.....	.....	125	.....	175	.....
Reese River	91.8		.....	.....	100	.....	....	.....

The precipitation during 1942-43 has been complex. The total snow and rain combined during the winter has been for the upper Humboldt 137.6, Little Humboldt 187.4, and Reese River 91.8 per cent of normal. The snow-cover, however, even at the higher levels has been only 91.4 per cent for the upper Humboldt and 122.1 per cent for Little Humboldt-Quinn River, and at the lower levels as little as 42.2 per cent on the upper Humboldt.

Since snow-cover is far more efficient than rainfall in creating runoff, the seasonal percentage of the snow-cover rather than that of the heavier precipitation should be chosen in making a forecast. Since, however, the snow-cover in the lower and relatively larger areas is scant or lacking, the average of the two should be adopted, or 66.8 per cent for the upper Humboldt. The effect of the precipitation will appear in that of the water-table built up at least in part from it.

On the basis of the excess flow of 250,000 acre-feet in 1942, due evidently to the high water-table, a similar excess can be expected the present year, distributed proportionately as before throughout the runoff-period even at high levels.

The above-normal shrinkage of the snow-cover in March was doubtless due to acceleration of melting from unusually high density and deficiency of precipitation during March.

During April the weather was warm and precipitation approximately normal. May has been both cold and deficient in moisture with consequent drying of the range. These factors will provide only minor corrections in the forecast when combined with the heavy correction for high water-table.

The residual snow on the Santa Rosa Range, the full length of the Ruby Mountains, and the Jarbidge Range indicates a steady flow fully normal and probably much greater for the remainder of the period from March to July.

The forecast of probable flow during March to July for the upper Humboldt at Palisade was 185 per cent of normal. Of this 168 per cent of normal has now (June 12, 1943) been attained. Two weeks of a major month and an entire minor month remain. It is hoped that present trends of weather with variation will continue in the Humboldt Basin until sufficient data for final conclusions can be assembled. (At the close of the runoff-season ending July 31, 1943, the percentage was 200, or more than double that of the snow-cover.)

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PREDICTION OF TEMPERATURE-DISTRIBUTION IN FROZEN SOILS

W. P. Berggren

There are evident obstacles to the accurate prediction of thermal conditions in soils. In the first place, the term "prediction" must be limited to determination of variations of temperature expected on the basis of observed or assumed initial distributions and subsequent surface-conditions. The great difficulty of measuring thermal properties, which are subject to complex variation with structure and packing as well as with moisture-content, remains the most severe limitation. Moreover, the migration of water during freezing is likely to invalidate the most painstaking determination of initial soil-properties.

The logical starting point for theoretical study of the problem of soil-freezing is the definition of an idealized system which will permit exact mathematical formulation. The analysis of such a system should not be regarded as a "theoretical solution" of the real problem, but as a description of the behavior of the ideal system, whose properties are recognized as differing from those of the actual problem [see 3 (Chapter 1) of "References" at end of paper]. Failure of the results to agree with observed performance of the real system must be charged to excessive idealization of the problem, rather than to shortcomings of the mathematical analysis. Improved agreement may be obtained by more realistic definition of the ideal system, until the complexity of the analysis becomes excessive.

The utility of the idealized analysis, though limited by the uncertainty of soil-properties and their variability with imposed conditions, should be apparent in at least three ways:

(a) As a guide to interpolation or extrapolation of observed soil-temperature variations under freezing conditions
(b) As an indication of the departure of soil-properties (including moisture-distribution during freezing) in situ from laboratory measurements on samples
(c) As a means of predicting the rate of freezing, particularly as influenced by the initial and subsequently-imposed conditions of temperature and the presence of snow or vegetation

Fortunately, the rate of increase of the depth of the frozen layer proves to be relatively insensitive to departure of field-conditions from the properties of idealized systems. Hence, predictions of rate of freezing will ordinarily be more reliable than those of temperature-distribution as a function of time.

The following analysis permits only approximate prediction of the insulating effect of snow or vegetal cover. The method tends to underestimate the retardation of the freezing-rate due to surface-cover. At this time, only a suggested means of attack on the rate of thaw-problem is offered. It is hoped that development of the analysis in these respects will eventually facilitate prediction of runoff and erosion.

Analysis of idealized system

The lectures of RIEMANN [5, 7] include the analysis of a one-dimensional liquid-solid system under transient thermal conditions. With alterations only in terminology and notation, the solution becomes applicable to the idealized problem of freeze-penetration in soils.

The ideal system is defined as a semi-infinite slab (bounded only by a single plane $x = 0$) of porous material through which a liquid, initially at a uniform temperature t_0 (above the freezing-point), is uniformly diffused. At a certain time (denoted by $\theta = 0$) the surface-temperature is reduced to and maintained at a sub-freezing value t_s. A frozen layer immediately begins to form at the surface $x = 0$, and its increasing thickness will be denoted by X.

The freezing-point of the liquid is indicated by t_f. Its latent heat of fusion (per unit-volume of matrix material) is denoted by L, and no volume-change is supposed to occur during freezing. The thermal properties of the frozen and unfrozen material will be identified by subscripts, as follows:

Property	Solid	Liquid
Thermal conductivity	k_1	k_2
Volumetric heat-capacity	C_1	C_2
Thermal diffusivity [= (k/C)]	a_1	a_2

The differential equations applicable in the solid and liquid zones are, respectively,

$$\frac{\partial t}{\partial \theta} = a_1 \frac{\partial^2 t}{\partial x^2} \quad \text{for } 0 < x < X \tag{1}$$

and

$$\frac{\partial t}{\partial \theta} = a_2 \frac{\partial^2 t}{\partial x^2} \quad \text{for } x > X \tag{2}$$

The initial conditions are

$$t = t_0 \quad \text{for } x > 0,\ \theta = 0 \tag{3}$$

$$X = 0 \quad \text{for } \theta = 0 \tag{4}$$

The fixed boundary conditions are

$$t = t_s \quad \text{for } x = 0,\ \theta > 0 \tag{5}$$

$$t \to t_0 \quad \text{for } x \to \infty,\ \theta > 0 \tag{6}$$

The conditions at the advancing boundary of the frozen layer will be

$$t = t_f \quad \text{for } x = X,\ \theta > 0 \tag{7}$$

$$k_1 \left(\frac{\partial t}{\partial x}\right)_{X-0} - k_2 \left(\frac{\partial t}{\partial x}\right)_{X+0} = L \frac{dX}{d\theta} \tag{8}$$

The temperature-distributions, at any time θ, in conformity with the foregoing conditions, are of the form

$$t = A_1 + B_1 G\left(\frac{x}{2\sqrt{a_1 \theta}}\right) \quad \text{for } 0 < x \leqq X \tag{9}$$

$$t = A_2 + B_2 G\left(\frac{x}{2\sqrt{a_2 \theta}}\right) \quad \text{for } x \geqq X \tag{10}$$

Magnitudes of the four constants in terms of conditions of the problem are given later under equation (14). The function G is the probability-integral, known also as the Gauss "error-function," and defined by

$$G(y) \equiv \frac{2}{\sqrt{\pi}} \int_0^y e^{-z^2}\, dz \tag{11}$$

Convenient tables of this function are available [11, 13]. It can be approximated fairly well (within about ten per cent) by $G(y) = y$, up to $y = 0.6$. The magnitude of the function then approaches unity as its argument becomes indefinitely large (see Table 1).

Table 1--The probability-integral

y	0.00	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00
G(y)	.0000	.2763	.5205	.7112	.8427	.9229	.9661	.9867	.9953

The thickness of the frozen layer is found to be proportional to the square root of time

$$X = 2\beta\sqrt{a_1 \theta} \tag{12}$$

Table 2--Magnitudes of β in the equation $X = 2\beta\sqrt{a_1\theta}$

$[(\sqrt{\frac{k_2C_2}{k_1C_1}}) \times (\frac{t_o - t_f}{t_f - t_s})]$	$L/[C_1(t_f - t_s)]$ = 0	0	1	5	10	20
	β for $(a_1/a_2) = 1.00$	β for $(a_1/a_2) = 1.82$				
0.10	1.195	1.130	0.578	0.299	0.216	0.155
0.20	0.978	0.915	0.540	0.291	0.213	0.153
0.50	0.684	0.635	0.455	0.271	0.203	0.148
1.00	0.477	0.442	0.361	0.241	0.187	0.141
2.00	0.305	0.285	0.257	0.197	0.162	0.127
5.00	0.1488	0.1425	0.138	0.124	0.112	0.0961
10.00	0.0807	0.0786	0.0779	0.0747	0.0714	0.0662

Table 3--Representative thermal properties and freezing-times ($\theta = \mu X^2$)
(For units, see Table 4)

Substance	Per cent moisture by volume	a	k	C	L	μ*
Fresh snow	10	0.04	0.12	3	900	....
Dry soil	0	0.012	0.19	16	0	220
Moist soil, frozen	...	0.031	0.68	22	....	....
Unfrozen	20	0.017	0.48	29	1800	280
Wet soil, frozen	...	0.042	1.21	29	....	....
Unfrozen	45	0.022	0.97	44	4000	330
Ice	...	0.048	1.34	28	....	....
Water	100	0.005	0.31	62	9000	510

*For $t_s = 23°F$, $t_f = 32°F$, $t_o = 50°F$.

where a_1 is the thermal diffusivity in the frozen zone and the dimensionless coefficient β is the positive root of

$$\frac{e^{-\beta^2}}{G(\beta)} - \sqrt{\frac{k_2C_2}{k_1C_1}}\left(\frac{t_o - t_f}{t_f - t_s}\right)\frac{e^{-(a_1/a_2)\beta^2}}{1 - G(\sqrt{a_1/a_2}\,\beta)} = \frac{L}{C_1(t_f - t_s)}\sqrt{\pi}\,\beta \qquad (13)$$

Representative magnitudes of the "growth coefficient" β, in terms of the dimensionless parameters $\sqrt{\frac{k_2C_2}{k_1C_1}}\left(\frac{t_o - t_f}{t_f - t_s}\right)$ and $\frac{L}{C_1(t_f - t_s)}$, are given in Table 2.

The constants which are to be substituted into equations (9) and (10) in order to determine the temperature-distributions in the frozen and unfrozen zones will be given by

$$\left.\begin{aligned} A_1 &= -(t_f - t_s), & B_1 &= \frac{t_f - t_s}{G(\beta)} \\ A_2 &= -\frac{(t_o - t_f)\,G(\sqrt{a_1/a_2}\,\beta)}{1 - G(\sqrt{a_1/a_2}\,\beta)}, & B_2 &= \frac{t_o - t_f}{1 - G(\sqrt{a_1/a_2}\,\beta)} \end{aligned}\right\} \qquad (14)$$

Solution of examples

In order to facilitate computation of the time required for a soil to freeze to a given depth, equation (12) is rewritten

$$\theta = \mu X^2 \qquad (15)$$

where the "freezing-time coefficient" $\mu = (1/4a_1\beta^2)$, has the dimensions time/distance^2 (inverse thermal diffusivity). In Table 3, estimated thermal properties of snow, dry soil, frozen and unfrozen soils at two conditions of moisture-content ("moist soil", 20 per cent by volume; "wet soil", 45 per cent by volume), and an ice-water system are given. Corresponding magnitudes of the freezing-time coefficient μ appear in Table 3 for assumed initial and surface temperatures $t_o = 50°F$ and $t_s = 23°F$, respectively.

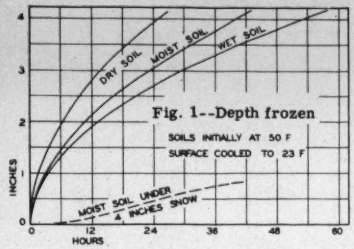

Fig. 1--Depth frozen

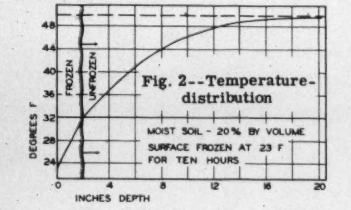

Fig. 2--Temperature-distribution

In the case of dry soil, the problem reduces to that of a semi-infinite slab whose surface-temperature is suddenly changed [3 (p. V-30) and 8 (pp. 46-48)]. The time required for the 32°-temperature to reach given depths is computed for comparison, although no latent heat or change of properties is involved. The rate at which a given temperature penetrates is proportional to the square root of time, as before.

The effect of a four-inch cover of fresh snow on the "moist" soil was estimated by computing the time required, under steady conditions, for the snow to conduct enough heat to lower its surface-temperature to 23° F, establishing a linear gradient to 32° F at the ground-level, plus removing the latent heat from given depths of the soil. Since this method neglects the heat removed from the unfrozen soil, the actual depth frozen under a snow or vegetal cover at any given time is certainly lower (possibly by 40 per cent) than the estimated depth.

Rates of soil-freezing, under the various conditions described above, are plotted in Figure 1. The temperature-distribution in the "moist" soil after ten hours, when frozen two inches deep, appears in Figure 2. The expressions for temperature in the solid and liquid zones are given respectively by

$$t_1 = [23.0 + 54.1\, G(0.90x)] \tag{16}$$

and

$$t_2 = [26.8 + 23.2\, G(1.21x)] \tag{17}$$

where x denotes depth in feet from the soil-surface.

Special adaptations of the analysis

For the special case in which the initial soil-temperature coincides with the freezing-point, the approximation described in the foregoing paragraph on snow-cover becomes almost an exact solution. STEFAN [12] obtains for this case, provided the latent heat of the material is large compared to its heat-capacity, the simple expression

$$X = \sqrt{(2k_1/L)\,(t_f - t_s)\,\theta} \tag{18}$$

Hence the coefficient β (equation 12) is given for this case by

$$\beta = \sqrt{C_1\,(t_f - t_s)/2L} \tag{19}$$

This eliminates the necessity of solving the transcendental equation (13). FRANKLIN [6] obtains surprisingly good experimental verification of computations performed by this method.

Another convenient simplification given by STEFAN, again for the case of the unfrozen material initially at the freezing-point, is the correction for time-variation in surface-temperature by replacing the product $[(t_f - t_s)\,\theta]$ in equation (18) by the integral of the varying temperature-difference $(t_f - t_s)$ over the time-interval concerned.

Since the heat-capacity of soils (unless the moisture-content is very low) is small compared to their latent heat of fusion, the solution of the original ideal system, equations (9) to (14), furnishes a fair approximation to systems in which the initial temperature-distribution is not uniform. The average initial soil-temperature, taken over a depth five to ten times the expected depth of freezing, should be substituted for t_o in the equations. The approximation is much better for evaluation of freezing-rates than for temperature-distributions in the unfrozen zone.

The only available analysis offering reasonable accuracy (within about one per cent) under the foregoing conditions is a graphical procedure based on the difference-equation method of E. SCHMIDT [9 (pp. 13-15)]. This method has been adapted to systems involving latent heats, but this work has not yet been published. The procedure, though tedious, will also handle the previously-mentioned complications of snow-cover and variable surface-temperature. It is, in addition, the only method sufficiently versatile to solve general problems involving rate of thaw.

The Stefan solution for the case of initial temperature at the freezing-point, equation (18), offers a convenient method of measuring thermal conductivity by freezing soil-samples under controlled conditions. This method may eliminate some of the difficulties introduced by moisture-movement on application of heat, as recorded in the work of PATTEN [10].

An abrupt change of temperature-gradient (slope of the temperature-distribution curve, as in Fig. 2) is to be expected at the boundary of the frozen layer. This condition is indicated by equation (8). There is, of course, no foundation for the supposition that the temperature must remain at or very near to the freezing-point in the region of this boundary, that is, the temperature-curve passes through the freezing-point without having zero slope. Since the rate of heat-transfer through the frozen soil is greater--because of the latent heat being removed at the boundary--the gradient is steeper in the frozen layer, in spite of somewhat greater thermal conductivity here than in the unfrozen region. When the instantaneous rate of freeze-penetration is known, together with measured temperature-distributions, equation (8) provides a useful check on the consistent relationship among the frozen and unfrozen thermal conductivities, the latent heat, and the supposed moisture-content of the soil.

Table 4--Nomenclature

(Subscripts 1 and 2 denote thermal properties of frozen soils and of unfrozen soils, respectively)

Symbol, unit or value	Meaning
a, ft^2/hr	Thermal diffusivity [a = (k/C)]
A and B in °F	Constants in the temperature-distribution equations (9) and (10)
C, (Btu/ft^3 °F)	Volumetric heat-capacity
e, 2.718+	Base of natural logarithms
G	Probability-integral as defined by equation (11)
k, (Btu/hr ft °F	Thermal conductivity
L, (Btu/ft^3)	Volumetric heat of fusion
t, °F	Temperature at any time and position
t_f, °F	Freezing-point of soil
t_o, °F	Initial temperature of soil
t_s, °F	Fixed sub-freezing surface-temperature
x, ft	Distance below soil-surface
X, ft	Thickness of frozen layer at any time
y, z	Symbols used in defining probability-integral
β	Growth-coefficient of frozen layer ($X = 2\beta\sqrt{a_1\,\theta}$
μ, (hr/ft^2)	Freezing-time coefficient ($\mu = [1/(4\,a_1\,\beta^2)]$
θ, hr	Time, measured from application of surface-temperature t_s

Conclusion

For a fixed sub-freezing temperature suddenly applied at the surface, the depth of soil frozen increases with the square root of time, as indicated by equations (12) and (15). Departure of the initial temperature-distribution from uniformity has little effect on the rate of penetration, because the soil heat-capacity is ordinarily small relative to the latent heat of fusion. The frozen layer increases at a smaller rate for wetter soils, because of greater heat of fusion and despite greater thermal conductivity.

The temperature-distributions in and beyond the frozen region are given respectively by equations (9) and (10), whose constants are defined by equation (14). In the frozen zone and for about an equal distance beyond, the temperature-distributions may for practical purposes be considered linear (through having different slopes in each zone). The effect of the surface-freeze is small enough to be undetected by ordinary measurements of temperature when a depth equal to about ten times the thickness of the frozen layer is reached.

No correction is attempted for the descent of moisture by gravity after freezing has begun at the soil-surface [1], or for alterations of the freezing-point due to pressure or dissolved salts. In accounts of frost-heaving phenomena, on the other hand, moisture is said to be drawn up from lower levels. The existence of some pore-water at sub-freezing temperatures is also cited.

An estimate indicates that with a four-inch cover of fresh snow the depth of freeze penetration for a given time is only about one-sixth as great (see Fig. 1). This confirms in a general way the observations of ATKINSON and BAY [2]. The foregoing estimate is believed to indicate a rate of penetration which is somewhat too rapid.

The solutions presented here do not offer a reliable means of predicting rates of thaw, though it might be reasonable to apply the square-root-of-time relationship for a limited time, after a sudden rise of the surface-temperature. It is hoped that this investigation will aid in the important study of thawing under various conditions of moisture and cover, with a view toward application to problems of runoff and erosion.

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DISCUSSION

J. E. CHURCH (Nevada Agricultural Experiment Station, Reno, Nevada)--It is a great satisfaction on the West Coast, where climate is diversified, to have a center as at Davis intensely interested in the physics of soil-moisture and its details.

At the East Lansing Meeting of the Central Snow-Conference, CHARLES L. McGUINNESS of the United States Geological Survey in his paper on "The importance of snow in relation to ground-water recharge" stressed the point that "when the ground is frozen there is an impermeable confining bed above the water-producing conditions essentially similar to those in formations carrying water under artesian pressure. As long as a continuous frost-layer is present recharge from above is effectually prevented."

Dr. ROBERT E. HORTON expressed serious doubts regarding the impenetrability of frost-zones by water and during the past spring melt-water was found to seep quite readily through snow-crusts. It is true, however, that if the snow or soil is sufficiently cold the melt-water will be frozen en route by it and itself form perched strata. Except in the latter instance, the snow is sufficiently porous to permit percolation. The dye Fuchsine, which remains dormant on dry snow but turns immediately red when wet, is a fascinating detector of water-movement in snow. Unfortunately, it leaches out in soil or at least in muck.

W. P. BERGGREN (author's closure to discussion)--Informal discussion has suggested the following supplementary remarks:

(1) The magnitude chosen for L, the volumetric heat of fusion, will be affected by migration of water during freezing and by the presence of unfrozen water below 32°F, in so far as these factors can be evaluated.

(2) It should be emphasized that the curves (Figs. 1 and 2) are sample results of the analysis of idealized systems, in which thermal properties, as well as imposed temperature-conditions (see Table 3), have been arbitrarily assigned.

(3) The applicability of Table 2 is quite general except for the assumption $(a_1/a_2) = 1.82$ (ratio of thermal diffusivity frozen and unfrozen), which is fairly insensitive to moisture-content of the soil. The purpose of this Table is to facilitate evaluation of equations (9), (10), and (12) for specific problems by giving directly the roots of equation (13). These roots (magnitudes of β) are expressed in terms of two dimensionless parameters which are evaluated readily from the conditions of the problem.

SNOW-STUDY PROGRAM AT SODA SPRINGS NEAR DONNER SUMMIT OF CENTRAL SIERRA NEVADA

J. E. Church

This report presents tentative conclusions on cooperative investigations of snow and snow-melting by the Nevada Agricultural Experiment Station and the United States Weather Bureau at Soda Springs, California. The undertaking is expected to lead to an improvement in the measurement of snowfall and to a better understanding of the hydrometeorological factors affecting the runoff from snow.

The observational work during the past season was made difficult by the interruptions normal to war time, although at all times the project had the full cooperation of the military. It is expected that this project will be continued and expanded until abundant data for dependable conclusions have been accumulated.

The study of snow at Donner Summit originated at the sessions of the International Commissions of Snow and Glaciers at Washington in 1939 through the queries of Carroll F. Merriam regarding the possibility of a critical temperature and density at which snow would suddenly and rapidly melt and the writer's interest in seeing the Stevens seasonal rain-and-snow gage put to a prolonged test in heavy and deep snow. Vernon E. Rupp, when hydrologic engineer of the Weather Bureau at San Francisco, joined in the latter desire and obtained permission from the Weather Bureau to install the Stevens type-W recorder at Soda Springs. The Leupold Stevens Instrument Company and the Weather Bureau bore the expenses of installation while the Experiment Station provided supervision during the winter.

In the summer of 1942 Merrill Bernard, Hydrologic Director of the Weather Bureau, with Vernon E. Rupp and Ray K. Linsley, met the writer at Lake Tahoe and proposed a continuation and expansion of the program, which was finally made formal in a cooperative agreement signed by the Weather Bureau and the Experiment Station.

The following studies have now been organized: (1) Efficiency of precipitation-gages and snow-surveying under severe mountain winter conditions; (2) the physics of snow-melting; (3) temperature in the snow; (4) changes in snow-texture. The two latter were suggested particularly by Phillip Light and Roy E. Lundquist.

Equipment--Originally at Soda Springs Station there was one platform provided by the Southern Pacific Company and a tower. On the latter was the Friez reconnaissance precipitation-recorder. On the former were the usual Weather Bureau cooperative instruments and the Stevens type-W recorder. The snow-survey was being conducted in a pasture 1,000 feet to the east. It seemed best to place as many instruments as feasible in the pasture because of the snow-course there but likewise to keep near the hotel the instruments that must be visited daily. Otherwise extreme snow-conditions might make it difficult to visit the instruments without far greater expenditure of time than available funds permitted.

Finally, in consultation with Bertram S. Barnes, Mr. Rupp's successor, two centers were de-

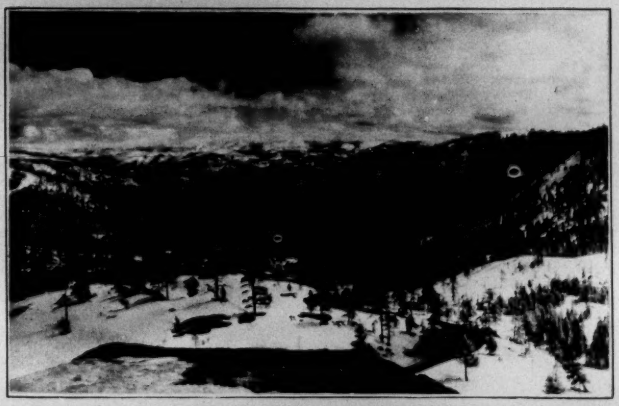

Fig. 1--View east from Donner Summit over Donner Lake and Mount Rose

Fig. 2--View west from Donner Summit over Lake Norden and Soda Springs at base of Beacon Hill beyond

veloped, one at the hotel and the other in the pasture. The original platform was extended to carry a series of precipitation-gages, sunshine-recorder, wind-vane and anemometer, and telethermoscope. A hygrothermograph was placed in the shelter with the maximum and minimum thermometers. The sunshine-recorder and wind-apparatus were connected with a triple register in the Post-Office Building by cable and wires furnished generously by other cooperators among whom was the Signal Corps of the Army. The standard rain-gage was retained as the basis of comparison of the catch of the various gages.

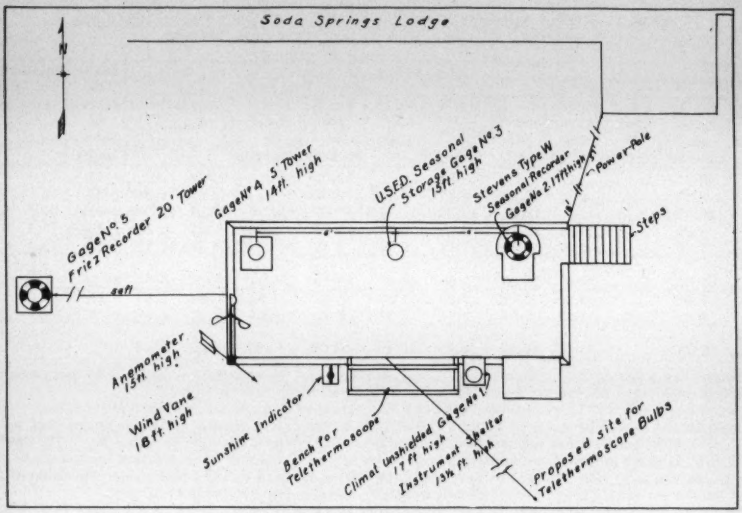
Soda Springs Lodge
Gage No. 5 Fritz Recorder 20' Tower
Gage No. 4 5' Tower 14ft. high
U.S.E.D. Seasonal Storage Gage No. 3 13ft. high
Stevens Type W Seasonal Recorder Gage No. 2 11ft. high
Power Pole
Steps
Anemometer 13ft. high
Wind Vane 18 ft. high
Sunshine Indicator
Bench for Telethermoscope
Climat Unshielded Gage No. 1 17 ft high
Instrument Shelter 13ft. high
Proposed Site for Telethermoscope Bulb

Fig. 3--Snow-gage arrangement on platform near Hotel, Soda Springs, California, December 1942

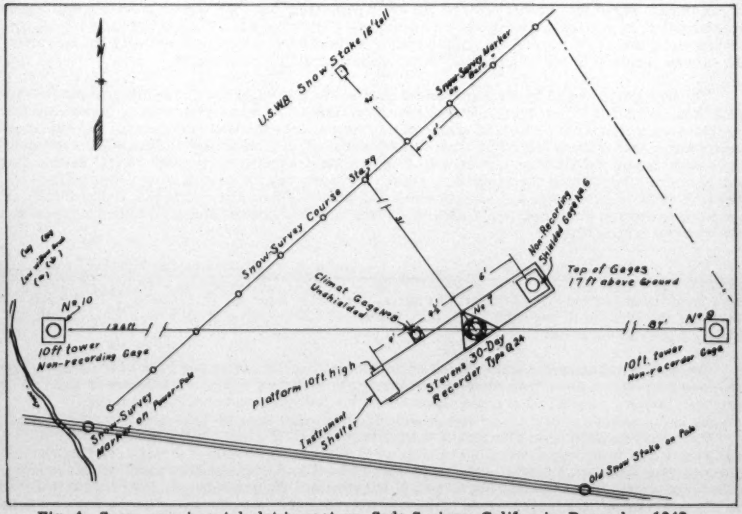
U.S.W.B. Snow Stake 16' tall
Snow Survey Marker
Snow Survey Course Stake
Non-Recording Shielded Gage No. 6
Top of Gages 17 ft above Ground
Climat Gage No. 8 Unshielded
No. 10
No. 9
10ft tower Non-recording Gage
Platform 10ft. high
Stevens 30-Day Recorder Type A-34
Instrument Shelter
Snow Survey Marker on Power Pole
Old Snow Stake on Pole

Fig. 4--Snow experimental plot in pasture, Soda Springs, California, December 1942

Table 1--Monthly summary of data for catch, in inches of water, obtained with precipitation-gages, Soda Springs, California, 1942-43

Month	Location										Depth on ground by snow-stake	Snow-survey, av. 10 measurements	
	Hotel					Pasture			10 feet above ground				
	No. 1, stand. unshielded	No. 2, type-W Stevens	No. 3, Army Eng. Corps	No. 4, check for No. 3	No. 5, Friez reconnaissance	No. 6, stand. shielded	No. 7, type-Q Stevens	No. 8, stand. unshielded	No. 9	No. 10		Depth	Water-equiv.
Nov.	12.81	.....	.....	.....	12.98	.....	12.60[b]	.....	.....	.....	18	17.7	8.3
Dec.	8.77	.....	9[b]	9.92[d]	9.57	9.41[d]	9.02	8.37[d]	8.05[d]	9.23[d]	34	32	13.0
Jan.	15.79	.....	17[c]	13.65	17.22	18.96	17.67	14.25	17.80	18.075	93	90.5	28.2
Feb.	3.96	.....	4.0+	5.19	4.85	4.75	4.85	3.89	5.47	5.31	86	77.7	32.5
Mar.	9.70	.....	9.0	9.84	11.63	9.545	9.37	8.695	10.545	10.425	84	78.5	38.4[e]
Nov.-Mar.	51.03[a]	.....	39.0[b]	38.60[b]	56.25	42.66[b]	53.51	35.21[b]	41.86[b]	43.04[b]	...	.....	.....
Apr.	2.60	.....	2.50	4.155	3.83	3.87	3.72	3.55	4.09	4.15	21	24.0	11.8
May	2.23	.....	2.88	2.38	2.34	2.23	2.22	2.05	2.37	2.39	0	0	.....
Dec. 1-June 1 adjusted	43.05	.....	45.96	45.42	48.33	50.62	47.05	42.67	50.18	51.44	...	.....	.....

[a]Equal 141.8 per cent. [b]Incomplete. [c]February 6. [d]Estimated. [e]Equal 98.2 per cent.

Notes: All gages except No. 1 and No. 8 were equipped with wind-shields.

Gages No. 9 and No. 10 were three feet deep for increased storage and lessened evaporation.

Comparison should be made by months rather than by the entire season, for some gages such as Nos. 3, 4, 6, 8, 9, and 10 were not installed until after the heavy precipitation of November. The Stevens type-W (No. 2) early suffered mechanical injury which has only recently been detected and repaired. The Army Engineers gage (No. 3) could be only approximately measured by stick and awaits the close of the season before the contents are drawn off and weighed. (Weight July 26, 1943, 47.38 in.)

All gages except No. 9 and No. 10 are fully 15 feet above the ground; No. 5 on the tower is somewhat higher.

In the pasture a Stevens type-Q recorder with tower was erected with a trestle containing two precipitation-gages, one unshielded and the other protected, together with a maximum and minimum thermometer, hygrothermograph, and an anemometer with dial but no triple register. Flanking the trestle were two towers containing rain-gages of three-foot depth but erected only ten feet above the ground because of lack of material. This in fact turned out fortunately.

The barograph owned by the Experiment Station was placed in the Post-Office to supplement other weather data. Other equipment has been accumulated as plans progressed. These are four metric anemometers, two standard anemometers provided by the Weather Bureau, and one standard anemometer loaned temporarily by Blue Hill Meteorological Observatory. Two telethermoscopes were provided by the Weather Bureau with supplementary housing by the Experiment Station that has provided also a dozen thermometers sealed in glass tubes for determining temperatures in snow. A drift-snow catcher and calorimeter have been designed and eight dyes, a pound each in quantity, have been procured. All instruments have now been tested and are ready for continuous use with the return of snow.

Every week since November through May the writer has visited Soda Springs and has usually remained two days each time and on occasion several days. The only regret is that he could not have been there continuously. Observers during the period were W. H. Sanders, until the Military Police of the Army took over the hotel, and, since that time, Arthur Couillard of Donner Summit Lodge, a quarter-mile west.

Ten precipitation-gages were placed under test during the winter and have been found to agree so closely with each other that admiration rather than criticism of their performance must be expressed. Table 1 shows in detail the closeness of the individual gages month by month.

Three conclusions from this list have been formed. (1) The precipitation at the two stations was practically identical, showing that the precipitation in this area is uniform. (2) The unshielded gages show a considerable catch-deficiency with respect to the shielded type and therefore the latter type should be considered the standard, but also that the gages nearer the ground catch more precipitation than those higher above. At first it was believed that the lower gages were being affected by drift-snow and for this reason the drift-snow catcher was designed. The uniform excess, even in spring when drift-snow was scant and rain was heavy, indicates, however, that the slowing

Table 2.--Wind-velocity, Soda Springs, California

Date	Wind-movement: General direction	Wind-movement: Miles for 24 hours preceding 5 p.m.: Near hotel	Wind-movement: Miles for 24 hours preceding 5 p.m.: In pasture	Wind-movement: Difference (hotel-pasture)	State of weather
1943					
Apr. 28	NW	88	82	- 6	Stormy
29	W	95	88	- 7	Clear
30	NW	90	100	+ 10	Part cloudy
May 1	NW	114	123	+ 9	Clear
2	NW	72	59	- 13	Part cloudy, clear
3	W	77	...	.....	Clear
4	NW	73	79	+ 6	Clear
5	W	102	102	0	Part cloudy
6	S	37	73	+ 36	Clear
7	NW	65	167	+102	Clear
8	E	284	380	+ 96	Clear
9	W	151	123	- 28	Clear
10	NW	100	125	+ 25	Clear
11	W	174	107	- 67	Clear
12	W	122	101	- 21	Clear
13	NW	4[a]	132[a]	(+128)[a]	Clear
14	NW	104	120	+ 16	Clear
15	NW	151	169	+ 18	Cloudy
16	SE	121	175	+ 54	Part cloudy
17	SE	169	255	+ 86	Clear
18	SE	139	226	+ 87	Clear
19	SE	72	173	+101	Cloudy
20	SE	86	63	- 23	Clear
21	W	88	121	+ 33	Clear
22	S	172	243	+ 71	Clear
23	SE	120	171	+ 51	Clear
24	SE	102	123	+ 21	Clear
25	W	124	111	- 13	Clear
26	W	54	121	+ 67	Clear
27	SE	89	169	+ 80	Clear
28	W	80	35	- 45	Clear
29	W	105	168	+ 63	Clear
30	NW	103	72	- 31	Cloudy
31	NW	174	166	- 8	Rain
Maximum[b]		284	380	+102	.....
				- 67	.....
Minimum[b]		37	35	0	.....
Average[b]		113	137	+ 24	.....
		Velocity in miles per hour			
Average daily Maximum[b]		11.8	15.8	+ 4.3	.....
				- 2.8	.....
Minimum[b]		1.54	1.46	0	.....
Average[b]		4.7	5.7	+ 1.0	.....

[a]Something wrong. [b]Omitting May 3 and 13.

of the wind nearer the ground permits more precipitation to enter. (3) The use of oil in the cans has apparently reduced the evaporation from them almost to nought. At one time an evaporation of 0.01 to 0.10 was noticed in the pasture with no evaporation whatever at the hotel. This slowing of the evaporation makes it feasible to use the ordinary open can in locations that can be visited only occasionally. The plan is being put in use immediately in Lamoille Canyon of the Ruby Mountains in determining the variation in precipitation with altitude up the slope of the canyon. The Tahoe National Forest also favors the plan in its desire to provide information to the public regarding precipitation in remote places in its forest that can be visited only occasionally.

The calcium chloride, except in cold weather and extremely heavy precipitation, serves well in keeping the contents sufficiently slushy to melt the accumulating snow. If stirred, its efficiency is much greater. In some of the cans this was not practiced, for a test of cans for long periods unattended was desired.

The wind-shields of the open type have shown their efficiency provided they are sturdily constructed. The open slats evidently atomized the wind as do trees in the forest and neutralized the air-currents. It is planned to attach streamers to the shields another winter to determine the direction of the wind as affected by the slant of the shields.

The shields, as constructed by Leupold-Stevens with chains of interlaced links, withstood a heavy gale January 21, 1943, that turned most of the other shields of open links inside out or tore them apart. Ashton Codd, who has rendered major service in establishing the project at Soda Springs during both years, installed sliding guide-wires on one of the gages (No. 10) to prevent the slats from being blown upward onto the can. This has had complete success in steadying the shield and holding it in position.

The question of the velocity of wind at which wind-shields are wrecked is a bit confused by the great divergence found between the velocity of the wind at Donner Summit and at Soda Springs Hotel during the above storm. The maximum velocity of the wind at Donner Summit was in excess of 100 miles hourly but at Soda Springs was as low as ten miles per hour. The observer, however, at the latter place estimated the wind at 60 miles per hour on the Friez tower, at which time he was hurriedly resetting the instrument. At the points somewhat more exposed than the anemometer, as on the Friez tower and in the pasture, the wind was undoubtedly much stronger. Table 2 affords comparison of the diurnal wind-movement at the two stations. The gale was blowing from the west and the pasture was in the axis of the wind.

Despite the freezing of the contents during January and the smothering of some gages under their own wreckage of shields and the leaving of some unprotected from the wind, the total precipitation was still reasonably uniform, probably because of the heavy precipitation already fallen when the wrecking occurred. Gages Nos. 1 and 6 had no shields and the shields of Nos. 2, 7, and 10 were unaffected. The last group was more sturdily built.

One pleasant surprise that came later was the realization that at least in intermittent storm and sunshine the orifices of the precipitation-gages can clear themselves. During the spring a most unusual phenomenon occurred at Soda Springs of snow so cohesive that it formed caps four to six inches high on all the gages. In fear lest this snow would be lost, the observer carefully trimmed these so that the cores fell into the tank. In the Friez recorder (No. 5) the resultant splash was 0.5-inch water on the record. Fortunately no effort was made to clear the gages in the pasture. On inspection it was found that the Stevens gage (No. 7) at the same time recorded a splash of similar amount. If the weather had been cold and the contents of the can had been frozen, the snow would probably have been wasted.

Recording-gages--Unfortunately recording-gages must be made sensitive in order to record the falling moisture and for this very reason they are subject to oscillation.

In the case of the Stevens type-W gage, the weigh-beam was so delicate that the instrument acted like a seismograph, responding when one ascended the platform or opened the iron door and retracing when the door was closed or one descended. For this reason a heavier oil in the damping-cup was used but further tests in the laboratory will be made in the summer of 1943 toward reducing the sensitiveness. If the record of precipitation hourly instead of at 15-minute intervals is satisfactory, as in the case of mountain precipitation and particularly snow, the contact-points might possibly be drawn farther apart. This gage has a capacity for double the 40 inches of precipitation that normally falls at Donner Summit. Through the use of a storage-battery sufficient heat was delivered to the collar to prevent any snow-accumulation beyond a fleck or two of frost throughout the winter. Its accuracy of catch, therefore, was extremely high. The batteries also did not freeze, indicating that primary cells if sufficiently strong and insulated may maintain themselves without serious deterioration from cold. If the sensitiveness of the instrument can be overcome, its length of period could easily be a year. To make the period this long, however, in case the precipitation is excessively heavy as it was the past winter, it will be necessary to develop a counterpoise on the weigh-beam to record the additional weight. At present the capacity of the weigh-beam is only 40 inches.

The Stevens type-Q recorder planned originally for only a month with a maximum catch of 24 inches of water is remarkably sturdy and steady though the pen is affected by climbing the tower.

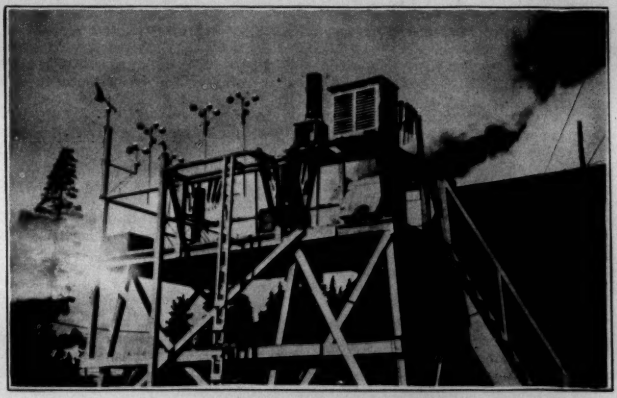

Fig. 5--Platform at Hotel, metric anemometers under test
(Trellis for cables telethermoscope)

Fig. 6--Buried in snow

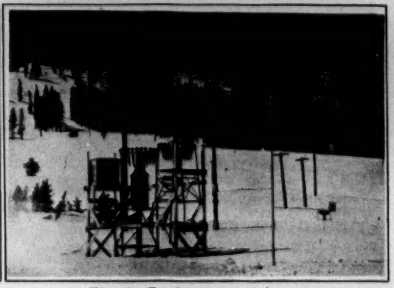

Fig. 7--Drift-snow catcher

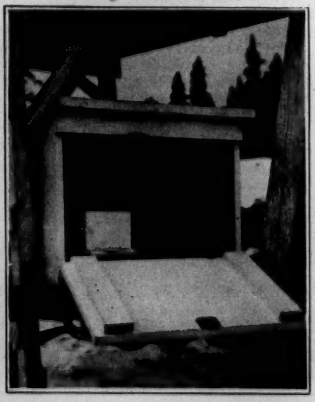

Fig. 8--Telethermoscope-case

Fig. 9--Telethermoscope-trellis for holding cables and thermal units in position

The pen--a barrel siphon--has not been filled since November 1942 and even now after seven months, when expanded by moisture in the air, is half full. The test will be continued to determine its maximum duration. With some increase in its capacity this instrument, driven by weight, should be capable of recording for six months except where the precipitation is extremely heavy. Even under the unusual conditions of this past winter it recorded for a month at a time without attention.

The Friez gage, which was built for the special purpose of recording detailed precipitation for short periods of time, naturally suffers under the severe conditions of the mountains and the height of its tower. However, its recording is accurate, except when the pen oscillates greatly in the wind or is thrown beneath the flange.

It now appears that the oscillation of the pens in all of the recorders is due to the suction of the wind passing over the orifice even more than to the vibration caused by the impact of the wind on the instruments themselves. The heavy gale of January 1943 evidently sucked the air upward in the Friez gage so greatly that the pen that had recently been set only an inch above the flange was caused to drop and catch below it.

Record-sheets in mountain areas or when not punctually removed should preferably overlap so that the pen can continue its trace without being caught either by the clip or the crease where the clip is inside the drum. It was found in the hygrothermographs that the pen would easily slip into the crack and be torn loose. The tendency of the sheets in the moist air to expand and wrinkle would likewise be reduced if the sheets overlapped. In this case a metal elastic band above and below would hold the sheet in position. In the case of the Stevens type-Q recorder, perforations in the record-sheet make it possible to hold the sheet in place by pins and so distribute the expansion and restrict it to limited areas.

Snow-surveying has been maintained at frequent intervals throughout the entire winter but no opportunity for the comparison of the accuracy of snow-surveying as compared with the catch of precipitation has been afforded because of the open winter, which has produced 141.8 per cent of normal precipitation and only 98.2 per cent of snow-residue. The value of both types of measurement is obvious, the former to show the gross assets and the latter the snow-residue on the eve of major runoff. Both types of measurements must be continued and should supplement each other.

The physics of snow-melting--The observation made last year that the snow-crust formed at 35°F as recorded a few feet above the surface was repeatedly confirmed the present year with crusts sometimes forming when the temperature was even at 40°F. Two additional thermographs have been obtained to make a series of traces of the temperature from the level of the snow upward to the level of the hygrothermographs at the two stations. Unfortunately these thermographs have divergent scales so that the comparison is not so easy. Several thermometers insulated in sealed tubes have been procured to determine the temperature at varying depths in the snow-cover itself from the surface to the ground.

Dyes--An old plan of using dyes has now been brought to fruition through the assistance of Dr. Phil E. Church of the University of Chicago. Several dyes were procured for a test. Most of them are satisfactory but one, the Fuchsine, was found to meet every requirement. It does not cause the snow to melt but lies dormant and green until it comes in contact with moisture when it immediately turns red. It is possible thus by sampling or cutting pits in the snow to determine the movement of moisture in the snow. It does not, however, penetrate soils or at least muck, but our present interest does not yet extend that far. Other visible detectors of water-movement in soils may be known or discovered.

Non-water-soluble powders have been found that can be placed on the snow to mark the various strata as they form at the surface or even later by aid of the snow-sampler.

The following case history will reveal the delicacy of this powder and its value in studying water-movement in the snow, thus assuring the qualitative study of this subject.

May 2, 1943, 8 a.m.

Planted dye (minimum temperature during night 28°F, present temperature 34°F); crust solid with frost.

Though pin-points of moisture attach themselves to the warm hand from frost, No. 6 (Fuchsine) is dormant except on three tiny crystals--even where scattered over frost-spicules. But slowly, after several minutes, occasional flecks of crimson dye appear like stars in the evening sky. Now the flush as of dawn in color as the Sun comes from thin clouds. The color travels up the individual

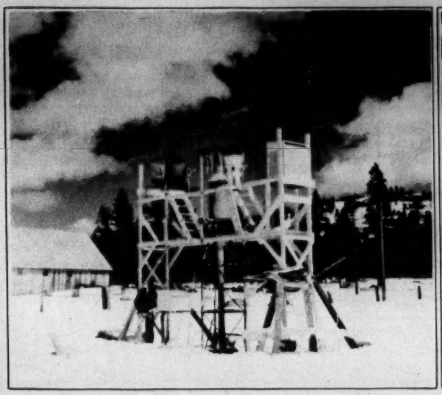

Fig. 10--Trestle in pasture with telethermoscope and thermographs on snow and midway upward to hygro-thermograph in shelter

Fig. 12--Snow on branch of pine susceptible to insolation

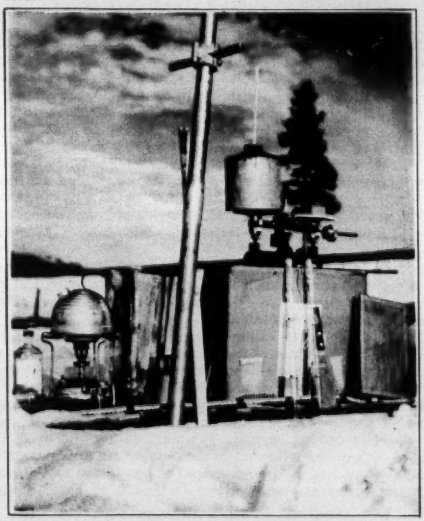

Fig. 11--Calorimeter-equipment

needles or spikes of the frost-stars and does not jump across. The frost is a tangle of rods, but only the topmost rods are colored, evidently where moistened by the Sun. The grains of dye deeper in the frost are still dormant. Now tiny flashes of color where a frost-rod has melted. Now they quicken and the red becomes more continuous as the water spreads.

A core of snow representing a cross-section of the snow-cover is cut and laid on the surface of the snow to test its moistness by sprinkling dye upon it. The core is only 12-1/2 inches long for the snow-cover is in its last stages. First 5-1/2 inches frozen dry and firm. The dye there is

Table 3--Summary of calorimetric data, Soda Springs, California, 1943

Equation: C in calories = [(2.45 in oz + hot water in oz)/snow in oz] [(temperature hot water in °C - final temperature in °C) - final temperature in °C]

No.	Date, weather[a]	Length core	Density snow	Grain-size	Temperature snow	Moisture[b]	Mass hot water	Temperature hot water	Mass snow	Final temperature	Calories per gram	Thermal quality
	1943	in	pct	mm	°F		oz	°C	oz	°C		pct
1	Apr. 25	3.5	?	2	32(?)	W	10.71	49	3.43	30.1	42.48	53
2	Apr. 26	15	53.3	1-2, ice 4	33	Mf	9.921	50.2	8.0	6.4	61.31	77
3	Apr. 27, sr	.....	.....	2	...	FW	9.921	20.9	1.5+[c]	16.0+[c]	16.39[c]	20[c]
4	May 2	17.3	68.0	2-4	35	W,CP	10.248	61	10.04	5.8	63.75	80
5	May 3, c, pc	6.5[d]	69.4	2-3	33[e]	MC	9.880	58.6	4.51	24.9	67.1	84
6	May 3	8.5[f]	51.5	3-4	33[g]	MP	10.71	63.4	4.38	30	70.2	88
5+6	.....	15.0	59.3	....	...	.....	.....	....	8.89	.....	.....	...
7	May 3	17.5[h]	48.7	....	...	Sd	10.285	62(?)[i]	8.52	5.4	78.9(?)[i]	99[i]
8	May 3	[j]	.....	4-10[k]	...	W	10.58	35.4	7.822	0.05[l]	58.7	73
8a	May 3	4[m]	31.2	4 est.	...	W	10.37	62.6	1.262[c]	49.5	84.1[c]	105[c]
9	May 7	3-5, total 15	47.9	1-2, max. 4 congealed	32.5[n] 32.7[o]	MW, CP	10.342	54.0	7.181	10.4	67.25	84
10	May 7, ss	10.7	53.9	1-2	32.7	MC[p]	10.059	51.0	5.77	13.0	69.38	87

[a]Symbols for weather: s = snow; r = rain; b = calm; pc = partly cloudy; sr = sunrise. [b]Symbols: W = wet; M = moist; D = dry; P = packs; C = crumbles; Mf = moist freezing, that is, MC; FW = firm wet slush; Sd = soil dripping. [c]Use with caution account small quantities; should try larger amount. [d]Upper 6.5 inches. [e]Eight inches down. [f]Lower 8.5 inches. [g]Twelve inches down. [h]Including ice button. [i]Probably 52°C on basis 52°C value for calories per gram is 64.03 and thermal quality 80 per cent; probably error delay in recording. [j]Scooped up at trestle--most nearly "latent heat." [k]Corn-snow, chunk of ice also. [l]A few crystals still unmelted. [m]At trestle, upper part of snow. [n]At 2.5 inches. [o]At 4.5 inches. [p]Though slightly WP.

Notes: Tests Nos. 9 and 10 made from residual snow; elsewhere ground bare. Snow had melted suddenly; depth May 4, 8 inches, May 5, 0 inch.

dormant (night temperature 28°F), except under the pressure of my hand, but then only on the outer crystals. Farther down the snow crushes and the moistness gradually increases (test the calories). The dye assumes a red color, well distributed through the core. The grain-size is one mm, increasing to clump-sizes of five to ten mm.

Calorimeter--The quantitative study of the heat of melting, already far developed by Walter T. Wilson, has now been initiated through the development of a home-made apparatus with the assistance of Dr. Samuel B. Batdorf of the Department of Physics of the University and John T. Ryan of the Engineering Laboratory. It comprises a coffee jar set in a tin-can and surrounded by rock-wool with a top covering of storage-battery plastic. The orifice is two inches wide, thus making it possible to drop snow-cores as cut by the snow-sampler readily into it. The thermos character of this jar is sufficient to cut out the influence of the outside air and leave the observer abundant time to determine the maximum and minimum temperatures in the experiment. By rolling the can to and fro in one's arms the water can be thoroughly mixed so that the readings are exact.

A weighing-scale graduated in grams, loaned by the Department of Chemistry, was recalibrated to record ounces (or inches) of water as measured by the snow-sampler with the Utah cutter. The capacity of the balance was increased from 11 ounces total to three times by employing a counterbalance that could bring the instrument into balance after the weighing of the jug, and the jug with hot water, thus leaving the last measurement to represent the weight of the snow.

A sheet of cross-section metric paper was used to determine the size of the snow grains, while the length of the core cut by the sampler, when weighed in the jug, gave its exact density. The temperature of the snow was determined by thermometers insulated in glass tubes. The snow

was classified as wet, moist, or dry, with a supplemental quotation as to whether it packed or crushed.

With this apparatus several measurements of the calories required to melt the snow were made. Those measurements about which no question of accuracy arose appear quite reliable in their mutual agreement. It is planned to continue the calorimetry of the snow throughout next season from new snow to weathered snow, and snow in the final stages of melting. Only careful operation seems necessary to acquire a large fund of reliable data. The data so far obtained with description are given in Table 3.

Melting and freezing--The effect of insolation in melting the snow is everywhere apparent, yet the duration of diurnal melting is relatively brief and apparently depends upon the combination of maximum and minimum temperatures, particularly upon the latter. Not so much the temperature of 32° F but the actual temperature of the snow below freezing determines the hour of the beginning of active melting in the morning while the temperature of freezing in the evening determines its immediate cessation. The day is, therefore, uneven in its divisions, for active melting may occur as late as 11 a.m. but always ends promptly when the Sun approaches the horizon.

Actually, as already mentioned, snow may freeze at an air-temperature of 35° or even 40°, depending upon the character of the snow and its lack of saturation. The snow-crystals are extremely porous and air-filled, which apparently accelerates loss of heat by radiation and hastens freezing. The coldness of the snow acquired during the night requires a considerable period to be brought to the point of melting, while little loss of heat is necessary to permit the melting snow to fall below the freezing-point. Therefore, instead of a 24- or even 12-hour day of melting, six hours in early spring at altitude of 7,000 feet represents the usual melting-period. This should have considerable bearing on the so-called daily rate of melting, based sometimes on experiments in the laboratory.

This theory should be checked out carefully this coming year. One or two quotations from field-notes will indicate the general trend.

December 9, 1942

Temperature last night 27° F; snow therefore not very cold.

New snow three inches deep, crystals one mm or smaller, cohere. Barometer rising.

On pine trees, snow concave or retracted from needles. Some drip and cohesion of trailing snow. By evening snow has largely disappeared from trees exposed to the Sun.

At $4^h\ 30^m$ p.m. temperature 35° F, sky thinly overcast (cirrus) or clouds broken, snow freezing. Crust 0.35 inch, the amount of melting during the day. Snow below crust is dry. Temperature 0.3 inch above snow 31° F.

At 5^h p.m. fog forming over valley. Relative humidity 98 per cent (?). Radiation despite humidity.

Place thermometer among pine needles under their snow-canopy and in free air (shaded) close by.

December 18, 1942

Temperature at $10^h\ 45^m$ a.m., 41° F. Frost-feathers still on snow at 11^h a.m., melting only on wood. Feathers only slightly moist to the touch. Melting-day therefore short, but snow where dirty already melting.

December 23, 1942

Dusk (5^h p.m. or later); current temperature, 36°.5 F; raining (no crust); temperature one-third inch above snow in rain 35° F.

[Note: Temperature of rain probably that of wet bulb or 35° F; melting of snow therefore slight.]

9^h p.m., temperature 33°-36° F, oscillating. Wind blew hat off. Thin layer of new snow on old; all soft. Rain must be turning to snow.

In front of hotel, snow-banks moist but congealing. There only 36° F at $9^h\ 45^m$ p.m.

$10^h\ 30^m$ p.m. On hotel porch 36° F. Incipient crust in front of hotel but snow still made a well-packed snowball. Therefore, snow congeals, though more slowly, at 35° F (head height) even when air is moist and sky is clouded, and radiation slowed down. The potency of radiation on congealing is therefore strong.

Notes: Humidity therefore seems to have no effect on the temperature of freezing but merely retards its coming. Then, for example, the temperature of freezing in damp New England is the same as in the arid West. However, the human discomfort in the former is greater. Test this in laboratory and in the Appalachians. In the lower mountains of the East, humidity may delay the fall of the temperature so greatly that freezing may even not occur during the night. Thus the hours of active melting per day may far exceed the eight or fewer per day usual to the Sierra Nevada.

Fig. 13--Formation of ice window-panes over pits following a windy day

Temperatures in the snow: Telethermoscope--Supplementing the use of the portable thermometers sealed in tubes is the telethermoscope, suggested by Phillip Light. The telethermoscope consists of a series of resistance-thermometers arranged at fixed levels in the snow and soil. The purpose of this instrumental set-up is to obtain simultaneous temperature-readings at frequent intervals throughout the snow and soil-column. This was installed at the hotel in order to make it easier for the observer to take readings once or twice daily. In soft snow the pasture seems too remote. However, at the hotel the saturation of the soil with drainage-water made it impossible to obtain soil-temperatures of any value.

Since the instrument as received was not built to withstand weather, a shelter-case was made for it with permanent switch and installation except that the battery was provided with a separate plug like a flat-iron so that it could be kept in warmth except when taken out for the individual observations.

To prevent the thermal units from being dragged down by the snow as it settled and thus distorting their location, a trellis was provided for holding the cables and the units firmly in position at fixed distances above the ground. The only difficulty with the present apparatus is that the length of the cables is insufficient to reach more than half-way up the platform whereas the instrument was planned for installation on the platform by the side of the sunshine-recorder.

When the snow had finally shrunk to a depth of less than three feet, the telethermoscope was moved to the pasture to obtain a longer series of test-readings. One thermal unit, the one used in the soil, seems to be defective. The others, though irregular in their readings, have been sufficiently uniform to merit the continuation of the experiment during the coming year. The instrument should afford a daily picture of the variation of the temperature at fixed elevations in the snow-cover. It is recommended that the instrument returned to Washington for readjustment be returned so that an installation can be made both at the hotel and in the pasture for the value of comparative measurements and more points of measurement. The extension of the trestle in the pasture by a cat-walk will make it possible to place the units where the soil-moisture is satisfactory and the snow unblown. Longer cables, however, should be provided to keep the instrument at all times above the snow.

Snow- and ice-types--Lundquist's classification of snow and ice has been developed and made practical by retyping it in the form of a book with pages protected against the snow and moisture by cellophane. To it has been attached a metric cross-section sheet for determining the sizes of snow-crystals. A scalpel for cutting snow, a large needle in a cork-handle, and a magnifying glass, complete the outfit for disengaging and magnifying the snow-crystals for study. Supple-

REPORT ON SNOW-TYPES

MONTH OF _____, 19___

(Place check in appropriate square for classification and date)

Type	Day of month																												
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
(I) TYPE OF SNOW- OR ICE-DEPOSIT																															
(A) Fresh accumulations																															
(1) Snowflakes																															
(2) Snow-grains																															
(3) Snow-pellets																															
(4) Sleet																															
(5) Hail																															
(6) Rime																															
(7) Glaze																															
(8) Frost																															
(B) Old deposits (or weathered)																															
(1) Fine powder-snow																															
(2) Coarse powder-snow																															
(3) Fine granular snow																															
(4) Medium granular snow																															
(5) Coarse granular snow																															
(6) Corn-snow																															
(7) Soft crust																															
(8) Hard crust																															
(9) Consolidated ice																															
(II) DEGREE COHESION OR COMPACTNESS																															
(A) Loose snow																															
(1) Fluffy																															
(2) Loose																															
(3) Initially cohesive																															
(B) Firm snow																															
(1) Firm																															
(2) Very firm																															
(C) Compact snow																															
(1) Compact																															
(2) Very compact																															
(D) Hard snow and ice																															
(1) Unusually compact snow																															
(2) Granulated crusts or honeycombed ice																															
(3) Solid ice																															
(E) Slush																															
(1) Firm slush																															
(2) Amorphous slush (fluid)																															
(III) QUALITY																															
(A) Dry snow																															
(1) Fresh snow																															
(2) Old snow																															
(B) Moist snow																															
(C) Wet snow																															
(D) Drowned wet snow																															

Notes: _____

Fig. 14--Specimen monthly form for report on snow-types

menting this is a report-book with a space for each day of the month and all of the months of the winter in which by means of a cross it is possible for the observer quickly to indicate the daily features of the snow. Ray K. Linsley has suggested that the measurements be made beneath the snow as well as on the surface.

Only two or three changes are recommended in the classification. (1) The term "old deposit" should be changed to "weathered snow" for snow-weathering can take place almost within a single day and change the character of snow completely from that it had when newly fallen. (2) The term "amorphous slush" should be changed to "fluid slush" as being more readily understood. (3) The grain-size could be more simply expressed in terms of mm than in any available divisions of the inch or the thickness of wire or sheet metal. While the inch is understood by all, 0.04 inch could scarcely be visualized and cannot be so readily expressed as one mm. Offsetting the unfamiliarity of the length of a millimeter is the scale in millimeters attached to the outlines on which the snow-crystals can be strewn and measured at a glance. Lundquist's chart should be in the hands of every observer of snow. A copy of the report-chart for field-use but without the millimeter-sheet is shown in Figure 14.

Supplemental reports--The subject of perennial snow and its ultimate glaciers, and snow-perils and avalanches have been quite fully treated and published in the Scientific Monthly for March and April 1943, and in the March 1942 issue a report was made on snow-sport and transport. These are all parts of the study at Soda Springs, including also 1942, when the investigations were initiated; the articles are copiously illustrated.

Nevada Agricultural Experiment Station,
Reno, Nevada

WESTERN SNOW-CONFERENCE

MINUTES OF BUSINESS MEETING

The annual business meeting of the Western Snow-Conference was called to order by J. C. STEVENS on June 16, 1943, at Corvallis, Oregon, following luncheon at the Benton Hotel. The meeting was then turned over to R. A. WORK, who presided.

A report [see Appendix A] from the chairman of the Executive Committee, FRED PAGET, was read to the group by Mr. WORK, who recommended that it be accepted as read and that FRED PAGET be given a unanimous vote of thanks by all members for his very strenuous work in holding the organization together during these trying times. It was so moved by Mr. CANFIELD, and the motion was seconded and carried.

With reference to discussion of drop in membership from 600 to 176, J. C. STEVENS asked: "With no dues, the question is whether those 600 members were bona fide members. Before dues were assessed, probably only 50 per cent were actual members." Dr. J. E. CHURCH, in answer to this comment, stated it had been the policy of the organization that anyone attending a meeting was automatically a member. Many, perhaps, had no permanent interest in the work; the 176 current members, however, are interested in the future of snow work. (Note: Members on November 1, 1943, numbered 190.)

WALTER E. JOHNSON, Acting Treasurer, submitted a report of the financial standing [see Appendix B]. The last examination of the books, January 15, 1942, which were audited and found correct, revealed a deficit of $370.22. The financial condition today, however, is better, showing a bank balance of $427.66 and an unencumbered balance of $77.66. Motion by ASHTON R. CODD that the Treasurer's report be accepted was seconded and carried.

No old business other than matters mentioned in Mr. PAGET'S report was brought up.

Election of officers--Mr. WORK referred to the policy expressed by vote of the membership of having all officers and members of the Executive Committee continue in office for the duration of the war, and following a short discussion said "It clearly is the sentiment of the group at this annual meeting today that the present officers be continued in accordance with former action."

In answer to G. H. CANFIELD'S question as to what area was involved--West Coast or Oregon--he was assured that the group represented the entire Western United States.

ASHTON R. CODD recommended allowing the appointment of other members to the offices of those who are taken into the armed service to keep the Executive Committee to its full membership. It was brought out that this provision is now in the By-Laws.

Name--In accord with a suggestion in Mr. PAGET'S report, J. C. STEVENS moved that the name of the organization be changed from Western Interstate Snow-Survey Conference to the shorter form of Western Snow-Conference. The motion was seconded and carried without further discussion.

Membership and dues--Mr. STEVENS brought up the fact that it had come to his attention that some members were not paying American Geophysical Union dues of $3.00 because they paid dues of $1.00 for Western Snow-Conference and received the Proceedings of both the Union's Section of Hydrology and Snow-Conference. He questioned how many would be willing to join the American Geophysical Union, with its dues of $3.00, and continue membership in the Snow-Conference as an affiliated branch. Perhaps some members might be lost to the Snow-Conference; however, even from a considerably smaller group the $3.00 instead of $1.00 per year would result in increased income. He asked if the Proceedings were available for purchase through any other channels.

Dr. CHURCH replied that the Proceedings were offered for sale at about $2.00 per volume, of which Western Snow-Conference provides only one part. A member of the Snow-Conference in this way gets only a part--probably material from one meeting--of what he would get were he to pay the full American Geophysical Union membership dues of $3.00. The Weather Bureau previously purchased a number of copies for distribution; however, this income is now reduced because of the number of their men who are becoming members and receiving individual copies through this channel.

Perhaps members who join the American Geophysical Union need not be required to pay the fee of $1.00 but the group could still remain as a sub-section of the American Geophysical Union, publishing with the Union in its Transactions under their supervision, and having the responsibility and privilege of voting for at least a part of the direction of things.

"I believe we should keep this group because of the concentration of interest," Dr. CHURCH said. "Let those who do not want to join the American Geophysical Union still pay only the dues of $1.00 to the Snow-Conference. Dr. FLEMING has published our Proceedings free and given us copies at $0.35 to be sold to interested organizations at $0.50, and so helping us financially. Though we appreciate his generosity, we should nevertheless reserve a place for those interested only in the snow."

W. W McLAUGHLIN, like Dr. CHURCH, did not want to see those interested only in the viewpoint of snow forced out of the present organization by an increase in dues. Many would get value received and more if they became members of the American Geophysical Union. He sympathizes with Dr. FLEMING'S ideals and generosity and likes to see records in a printed form, but still he prefers the idea of keeping members in the Snow-Conference and then encouraging the members to join the American Geophysical Union, even at the cost of $4.00 instead of $1.00.

Mr. WORK said "We want to keep 176 members and also encourage more to join and pay their dues. It seems necessary to continue solicitations from power-companies, experimental stations, and other interested organizations which have supported the work. Along with that we will work with the Committee on Membership of the American Geophysical Union under WILLIAM LANG in an effort to sometime reach the goal of 500 new American Geophysical Union members."

A count of hands revealed that, of the 25 present at this Western Snow-Conference meeting, 12 were members of the Union.

ELMER FISHER of the Weather Bureau office at Portland, raised a question concerning the membership of organization representatives. Mr. WORK replied that voting membership has nothing to do with individual membership--a man may be a voting member for an organization such as the Weather Bureau and still not be a member himself. Were he to pay his dues, he would be permitted to cast two votes--one for the organization and one personal vote. Mr. WORK urged that interested men join the Western Snow-Conference (six new members came in).

Mr. McLAUGHLIN pointed out that the subscriptions made by the Weather Bureau and others are for copies of the printed report, at a certain amount per copy--getting one vote for perhaps a subscription of $75.00, the same as an individual member gets for $1.00. However, of course, they receive the desired copies of Transactions for distribution.

ASHTON R. CODD asked how many members who belonged to Western Snow-Conference also belonged to the American Geophysical Union. Exact figures were not at hand, but Dr. CHURCH

said that if his memory of Mr. PAGET'S record served him correctly about one-third of our members were also members of the Union.

In regard to the goal of 500 new members, Dr. CHURCH said that the count was on a retroactive basis, going back about one year. Invitations to membership are being sent out from Washington, and WALDO E. SMITH has been extremely active in this work. We should be more active, he said, and get the names in first before they are sent back East for selection. Mr. STEVENS brought proposals for membership to the meeting, and any member present who wished to join was urged to fill out these and give them to Mr. WORK so that they might go through the Snow-Conference.

Mr. STEVENS commented, "The question cannot be settled now. It should be put back in the lap of the Executive Committee with the statement that it is the consensus of this meeting that we do nothing to upset the individual and organizational memberships in the Western Snow-Conference and that we try to urge people voluntarily, if they are interested, to join the American Geophysical Union and pay the double dues. We cannot--we should not--upset the Western Snow-Conference. It should be passed on to Mr. PAGET to pass on to the Committee that we should not in any way disturb the Snow-Conference but have as many as want to join the Union--encourage them to join both, not oust them if they do not join the Union." It was the unanimous opinion that this information be passed along.

It was W. W. McLAUGHLIN'S suggestion that many did not realize what they would get for their membership in the American Geophysical Union and that it would be well for the Secretary to get out some information on this. V. H. GOODNIGHT, Corvallis City Engineer, suggested some propaganda on the Western Snow-Conference, as well. He said to him it was something new, and at the moment he was "on the fence" concerning joining it or the Union.

Mr. WORK read a letter from Mr. LANG asking that an announcement be made concerning the benefits of membership in the American Geophysical Union and stressing the desirability of having applications pass through the Western Snow-Conference.

It was brought out that members receive the latest work in the science of natural phenomena through the Proceedings of these groups. Mr. McLAUGHLIN stated that the Executive Committee should be confronted with the problem of spreading this information to interested people. It was moved by Mr. WORK that the Western Snow-Conference go on record today as strongly in favor of the Executive Committee considering all feasible ways and means of increasing the membership of the Western Snow-Conference by extolling its merits to those who should be in it; the motion was seconded and carried.

Mr. McLAUGHLIN moved that a vote of thanks to the hotel management was in order for the excellent luncheon, the meeting space provided, and the service which made this such an enjoyable meeting. Mr. WORK extended the thanks to include the Section of Hydrology.

Those registered at the Corvallis Meeting are noted with addresses in Appendix C.

Meeting adjourned.

JULE CLAIRE WEST
Secretary

APPENDIX A--REPORT OF THE CHAIRMAN OF THE EXECUTIVE COMMITTEE OF THE WESTERN SNOW-CONFERENCE ON ACTIVITIES FOR THE PERIOD JANUARY 15, 1942, TO JUNE 10, 1943

To Members of the Western Interstate Snow-Survey Conference:

Since our last meeting at Pasadena the affairs of your Conference have moved smoothly along. Herewith I submit a report summarizing all the facts and figures relative to our activities during the past year and a half.

Salt Lake City Meeting--On April 9, 1942, following a suggestion from Dean CLYDE, the Executive Committee was circularized asking their opinion as to whether the proposed meeting at Salt Lake City should be proceeded with or whether, on account of unsettled war conditions, it should be cancelled. The resulting vote was: For holding meeting, 3; for cancellation, 16; noncommittal, 1. Because of the prevailing sentiment favoring cancellation, the meeting was called off.

Election of officers--Soon after the Pasadena Meeting, steps were taken in accordance with the By-Laws of the Conference toward holding the bi-annual election of a new Executive Committee. This had proceeded to the stage of appointing a Nominating Committee when a suggestion was made that the Executive Committee be asked their opinion as to whether or not a new election should be held, or whether it would be best to retain the present officers for the duration of the war. The voting in response to this question was: Retain present Committee, 14; elect new Committee, 4; not voting, 2. The membership was later asked to confirm this decision of the Executive Committee to allow the present Committee to remain in office. Confirmation was given with a vote of yes, 264, and no, 11.

Dues--At the Business Meeting of the Pasadena Conference, it was decided to poll the membership to determine the sentiment as to whether the Conference should go on a dues-paying basis of $1.00 per year, or whether it should affiliate with the American Geophysical Union with dues per member of $3.00 per year. The Chairman appointed a Committee to prepare a circular for submission to the membership. The Committee was composed of: J. E. Jones, Chairman; W. A. Lang; H. P. Boardman; and Merrill Bernard. This proposition was finally submitted to vote and the returns were:

Item	Yes	No	No vote
$1.00 membership	197	45	49
Affiliate with American Geophysical Union	129	87	75

As a result of this vote, a ballot was mailed March 2, 1942, submitting to the membership a proposal for changing the By-Laws to permit the collecting of dues from each member. This amendment was approved with a final vote of 175 to 5.

Membership--In accordance with the amended By-Laws, a circular was sent January 4, 1943, to some 600 individuals, then being carried on our Conference membership-rolls, advising them that dues of $1.00 for 1943 were due and payable. To date 28 per cent have replied and paid their dues. Our paid-up membership now totals 176.

Cooperation with American Geophysical Union--The long history of cooperation and aid given this Conference by the Section of Hydrology, American Geophysical Union, is well known to all of us. Dr. FLEMING, General Secretary of the Union, has extended to the Conference many favors. With the formation of the Great Lakes Snow-Conference and the Eastern Snow-Conference, Dr. FLEMING has made a proposal that if, through the three Conferences, 500 new names can be added to the American Geophysical Union, he will, without cost to the Conferences, undertake to publish all of their Transactions. The 500-goal is a far one, and not very much progress in its direction will probably be made during the war, but in order to make a start in the right direction, a Committee has been appointed to secure as many members as possible for the American Geophysical Union. This Committee is composed of WILLIAM LANG and JAMES E. JONES, both of Los Angeles. A recent communication from Mr. LANG carries the names of seven new members for the American Geophysical Union who have been secured through the Snow-Survey Conferences, and have been forwarded to his Committee for processing.

Treasurer--At the time of the Pasadena Meeting, the Chairman of the Executive Committee was also acting temporarily as Treasurer, substituting for CARL ELGES, our former Treasurer, now a Lieutenant-Colonel in the Coast Artillery.

After it had been decided to continue the Executive Committee in office for the duration, the Chairman tried to find someone else to take over the duties as Treasurer. No willing hand was held out, so your Chairman perforce has continued to pack the load.

Our financial condition is now at the highest peak since the Conference was initiated. This is due to a combination of circumstances: The low cost of the brief Transactions of the Pasadena Meeting; the generosity of the interested organizations who continued their usual annual subscriptions in spite of the abbreviated size of the Transactions; and to the considerable dues collected from the membership. At the time of the Pasadena Meeting, we were in debt $370.22. We now show a balance of $77.66 to the good.

Today there is in the bank account of the Conference a total of $427.66. Of this, however, $350.00 is ear-marked for Dr. CHURCH, to repay a loan made by him to the Conference a few years ago. Dr. CHURCH, in his usual magnanimous manner, has requested that the Conference temporarily retain this money, delaying payment to him until we are sure that we have surmounted our financial difficulties. It is hoped that by restricting the amount of matter to be published in the 1943 Transactions, and a diplomatic appeal to our annual subscribers, we may make our 1943

operations stand on their own feet, and when we do, we can probably then persuade Dr. CHURCH to receive back the money he so generously loaned the Conference.

Change of name--It has been proposed to change the name of this organization from the Western Interstate Snow-Survey Conference to the shorter, more convenient form of Western Snow-Conference. Fourteen members of the Executive Committee have replied to a poll recently submitted to them on this question. The fourteen were unanimously in favor of having the name changed to the shorter form. Although reference to our organization by the longer term is contained in the By-Laws, no statement appears that the Conference definitely shall be known by this name. Curb-stone legal talent is of the opinion that, because of this, it will not be necessary to go to the membership to obtain formal permission from them to change the name. It would be appreciated, however, if this desire for the short name expressed by the Committee could be approved by the members at the Corvallis Meeting, and if so approved, the name Western Snow-Conference will automatically be adopted as the current name for our organization.

Corvallis Meeting--When the holding of the Corvallis Meeting was suggested, a poll was made of the members of the Executive Committee to determine how they felt about it. The vote of the Executive Committee showed a majority favoring the meeting. Mr. WORK, Chairman of the Executive Committee of the North Pacific Area, was thereupon notified to work along with Mr. STEVENS of the American Geophysical Union and MURRAY LUCK of the American Association for the Advancement of Science to arrange the meeting at Corvallis. Early in June, Mr. LUCK advised us that, due to reasons beyond his control, the American Association for the Advancement of Science could not participate in the meeting. Plans for the meeting had by that time progressed to such a stage that the Section of Hydrology of the American Geophysical Union and the Snow-Conference felt that it was best to proceed with the meeting despite the unexpected withdrawal of the American Association for the Advancement of Science.

Comments by the Chairman--Your Chairman regrets that he has not found it possible to attend the Corvallis Meeting, and that he can not be with you tonight. However, he shares with you your continuing interest in the problems of snow.

FRED PAGET, Chairman
Executive Committee

APPENDIX B--REPORT OF TREASURER OF WESTERN SNOW-CONFERENCE

June 10, 1943

The last examination of the Treasurer's accounts was made on January 15, 1942. Audited and found correct by VERNON GIVAN and JERRY CHRISTIANSEN, the status of the finances at that time was:

Assets			
Bank balance		$155.87	
Accounts receivable			
Utah Experiment Station	$25.00		
United States Weather Bureau	75.00	100.00	$255.87
Liabilities			
Owing to Dr. J. E. Church		$422.46	
Owing to American Geophysical Union		203.63	626.09
Amount in debt			$370.22

Today our financial condition is better. The Balance Sheet shows:

Assets		
Bank balance as of June 10, 1943	$427.66	
Liabilities		
Owing to Dr. J. E. Church	350.00	
Unencumbered balance		$ 77.66

Receipts and disbursements since January 15, 1942, have been as follows:

Receipts		
Subscriptions for Transactions from interested agencies	$412.50	
Membership fees	176.00	$588.50
Disbursements		
To American Geophysical Union for supply of Transactions	$168.43	
Partial refund of loan to Dr. Church	72.46	
Postage, stationery, and printing	75.82	$316.71
Receipts exceeded disbursements by	$271.79	
Old bank balance, January 15, 1942	155.87	
New bank balance, June 10, 1943		$427.66

For those who may be interested in the exact details of income and expenses since the Pasadena Meeting, they are as follows:

Receipts				
1942				
Jan. 31	Colorado River Water Conservation District	$ 25.00		
31	Utah State Agricultural College	25.00		
May 19	Library, Soil Conservation Service	17.50		
25	U.S. Division of Irrigation	50.00		
Nov. 27	Tulare Lake Basin Water Storage District	10.00		
27	California State Division of Water Resources	25.00		
Dec. 7	Nevada Irrigation District	5.00		
10	Kern County Land Company	10.00		
31	Southern California Edison Company	25.00		
1943				
Jan. 4	Ten membership fees	10.00		
13	California-Oregon Power Company	25.00		
13	City of Los Angeles	25.00		
13	Washington Water Power Company	25.00		
13	East Bay Municipal Utility District	10.00		
13	Forty membership dues	40.00		
15	Twenty membership dues	20.00		
18	Twenty membership dues	20.00		
18	Oregon Agricultural Experiment Station	25.00		
21	Thirty membership dues	30.00		
22	Metropolitan Water District of Southern California	25.00		
22	Three membership dues	3.00		
Feb. 5	City and County of San Francisco	10.00		
5	Ten membership dues	10.00		
10	Twenty membership dues	20.00		
19	Six membership dues	6.00		
19	Pacific Gas and Electric Company	25.00		
19	Bonneville Power Administration, Portland	25.00		
Apr. 1	Eleven membership dues	11.00		
5	Los Angeles County Flood Control District	25.00		
June 9	Six membership dues	6.00		
	Total receipts			$588.50
Disbursements				
1942				
Jan. 21	Programs for Pasadena Meeting	$ 4.90		
Feb. 27	American Geophysical Union, 1941 Transactions	136.51		
May 19	Postage for mailing out circulars	2.96		
19	Refund of postage paid by Dr. Church	28.40		
22	Postage on election ballots	9.57		
25	Paid to Dr. Church on outstanding loan	72.46		
Nov. 13	Postage on 1942 Transactions	9.75		
27	American Geophysical Union, 1942 Transactions	31.92		
Dec. 31	News Publishing Company for membership cards	10.09		
1943				
Jan. 4	News Publishing Company for envelopes	1.15		
6	Postage on notices of membership dues	9.00		
	Total disbursements			$316.71
	Receipts exceed disbursements by	$271.79		
	Bank balance as of January 15, 1942	155.87		
	Total current assets			$427.66

WALTER E. JOHNSON, Acting Treasurer

APPENDIX C--REGISTRATION AT JOINT MEETING OF SECTION OF HYDROLOGY, AMERICAN GEOPHYSICAL UNION, AND WESTERN SNOW-CONFERENCE AT BENTON HOTEL, CORVALLIS, OREGON, JUNE 16, 1943

John M. Allison, Meteorologist, Army Engineers, 628 Pittock Building, Portland, Oregon
Bertram S. Barnes, Regional Engineer, U. S. Weather Bureau, San Francisco, California
W. P. Berggren, Assistant Physicist, Agricultural Experiment Station, University of California, Davis, California
G. H. Canfield, District Engineer, U. S. Geological Survey, 606 Post-Office Building, Portland, Oregon
R. W. Childreth, P. O. Box 315, Gladstone, Oregon
J. E. Church, Nevada Agricultural Experiment Station, Reno, Nevada
Ashton R. Codd, Hydrologic Engineer, U. S. Weather Bureau Regional Office, Boeing Field, Seattle, Washington
Elmer Fisher, Unit Supervisor (Hydrology), U. S Weather Bureau, Portland, Oregon
V. H. Goodnight, City Engineer, City Hall, Corvallis, Oregon
Edw. L. Greene, Assistant General Superintendent, Kaiser Company Inc., Vancouver Yard, 3205 F Street, Vancouver, Washington
Lyman C. Huff, Junior Geologist, Ground Water Division, U. S. Geological Survey, 212 Old U. S. Court House, Portland, Oregon
Walter E. Johnson, Assistant Engineer on Hydrology, Washington Water Power Co., 825 Trent Avenue, Spokane, Washington
Karl O. Kohler, Jr., Chief, Regional Engineering Division, Soil Conservation Service, Pacific Building, Portland, Oregon
Paul E. Lattner, Chief Design Engineer, Kaiser Company Inc., Vancouver, Washington; 2509 NE Flanders, Portland, Oregon
Norbert Leupold, Engineer, U. S. Army Engineers, 628 Pittock Block, Portland, Oregon
Ray K. Linsley, Jr., Associate Hydrologic Engineer, U. S. Weather Bureau Office, Sacramento 9, California
James C. Marr, Irrigation Engineer, Division of Irrigation, Soil Conservation Service, Box 835, Boise, Idaho
W. W. McLaughlin, Chief, Division of Irrigation, U. S. Department of Agriculture, Box 180, Berkeley, California
D. J. McLellan, Engineer, State Reclamation Commission, 1100 Chemeketa Street, Salem, Oregon
C. E. Mohler, Assistant Engineer, U. S. Bureau of Reclamation, 460 N. High Street, Salem, Oregon
A. P. Newberry, Puget Sound Power and Light Co., Seattle, Washington
Clarence Pedersen, Engineer, U. S. Army Engineers, Portland, Oregon
J. C. Stevens, Stevens and Koon, Consulting Engineers, Spalding Building, Portland, Oregon
George C. Taylor, Jr., Assistant Geologist, U. S. Geological Survey, Ground Water Division, 212 Old U. S. Court House, Portland, Oregon
Stanley Tripp, Engineer and Construction Foreman, City Water Works, 602 North 19th Street, Portland, Oregon
R. H. Wahle, Bonneville Administration, Portland, Oregon
R. A. Work, Irrigation Engineer, U. S. Division of Irrigation and Oregon Experiment Station, P. O. Box 1149, Medford, Oregon

REPLY BY R. H. WAHLE TO QUERIES OF BERTRAM S. BARNES (see p. 28)

R. H. WAHLE (Communicated October 25, 1943)--I do not know whether this method is of any value as regards such rivers as the Ohio. The method has been applied only to the Columbia River. It has been used only for streams where snow is a large factor. Possibly the good results achieved are because runoff is largely due to the snow-factor. At the moment I am unable to state any possible relation between nature and extent of snow for the first six months and runoff for the second six months.

Note: It may be of interest to note that the actual runoff, as computed in October, 1943, stands at 155,335,000 acre-feet for the year ending September 30, 1943. The pattern-behavior forecast for 1942-43 indicated a peak of 685,000,000 cfs at Bonneville with the total runoff set at 155.000,000 acre-feet.

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